The Next-Generation Firefighter: The Evolution of Technology

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Abstract

In 2013, United States fire departments responded to around 1 240 000 fires, accounting for 106 firefighter deaths. These fires also resulted in 3240 civilian deaths and an estimated $11.5 billion in property damage. When responding to fires, firefighters must be aware of their surroundings, informed on the situation they are responding to, and able to communicate effectively and efficiently with each other. Achieving those goals improves firefighter safety and ability to save civilian lives and minimizes cost due to property damage. This report discusses how using off-the-shelf consumer products, one can begin to visualize the next-generation firefighter, who is connected, protected, and fully aware by identifying the gaps between today's commercial technologies and the needs of the next-generation firefighter. Research is needed to expand capabilities in these areas.

Foreword

In the summer of 2015, PSCR added student engineers to the team through the Summer Undergraduate Research Fellowship (SURF) and Pathways programs at NIST. Our goal in bringing students on board was twofold: first and foremost, engage a new generation of engineers, scientists and mathematicians in innovative thought around public safety communications. Second, leverage the principles and approaches being taught in our Nation's universities that many of us "old dogs" in PSCR have long since forgotten. These students have been a breath of fresh air.

For our first generation of student engineers, we had a very simple request: get to know the public safety community we serve, and see what they are thinking about state of the art technology. Find ways we can help them communicate more effectively in the future. We did not want to constrain their thinking by strictly defined outcomes, but instead allowed them the freedom to execute a project of their design. We could not be more proud of their results. They settled on the fire service due to the diversity of services it provides to the public. Then, they jumped right in. Our students walked through the doors of the Boulder Fire Service and began asking questions. Through a series of ride-along trips and conversations, they began to explore technology with their stakeholders and to identify on a personal level with the daily challenges faced by firefighters.

The thoughts and information represented in this paper are those of our student engineers who are getting to know the public safety community. The products and technologies within the report do not represent PSCR's endorsement of any particular brand or company, but instead they convey a great conversation between our students and public safety. We hope you enjoy their report and find the public safety information conveyed herein to be informative.

Tracy McElvaney

Contents

List of Figures

List of Tables

Acronyms

- **BFRD** - Boulder Fire-Rescue Department
- **BM** - Biometric
- **BP** - Blood Pressure
- **CORA** - Colorado Open Records Act
- **CPRA** - California Public Records Act
- **CTL** - Communications Technology Laboratory
- **dBA** – A-weighted Decibels
- **dBm** – Decibel Milliwatts
- **DIY** – Do-It-Yourself
- **EL** – Electroluminescent
- **FRS** – Family Radio Service
- **GMRS** – General Mobile Radio Service
- **GLONASS** - Global Orbiting Navigation Satellite System
- **GPS** - Global Positioning System
- **HAZMAT** - Hazardous Materials
- **HUD** – Heads-Up Display
- **IC** - Incident Command
- **ICP** – Incident Command Post
- **IoT** - Internet of Things
- **ITS** - Institute of Telecommunications Sciences
- **LED** - Light Emitting Diode
- **LTE** - Long Term Evolution
- **NFC** - Near Field Communication
- **NFS** - National Forest Service
- **NIOSH** - National Institute for Occupational Safety and Health
- **NIST** - National Institute of Standards and Technology
- **NOAA** - National Oceanic and Atmospheric Administration
- **NTIA** - National Telecommunications and Information Association
- **OSHA** - Occupation Safety and Health Administration
- **PL** – Photoluminescence
- **PPE** - Personal Protective Equipment
- **PSCR** - Public Safety Communications Research
- **RF** - Radio Frequency
- **RMS** - Remote Monitoring Software
- **SCBA** - Self-Contained Breathing Apparatus
- **TIC** - Thermal Imaging Camera
- **TOPO** - Topography/Topographical
- **UPF** - Ultraviolet Protection Factor
- **UV** - Ultraviolet
- **UAS** - Unmanned Aircraft System
- **UAV** - Unmanned Aircraft Vehicle

1 Introduction

Consumer technologies are advancing and growing at unprecedented rates. Unfortunately, innovation for first responders tends to follow a much slower path. Currently, public safety technology has room for improvement in the areas of health, safety, information availability, and communications. As Long Term Evolution (LTE) networks become more prominent and related technologies are developed, the Internet of Things (IoT) continues to grow, and progressively more data is continuously available at the touch of a button. These same advances found in commercial technology for communications and information technology must be applied to first responders to ensure that they are protected, connected, and fully aware.

This report represents an initial investigation into the state of current first responder technology, as well as currently available consumer technology that could be applied to first responder needs. Due to the scope of the problem, this paper focuses specifically on the technologies of firefighters. Available technologies are identified, and the gaps between the current state of such technologies and where the technologies need to be for implementation with firefighters are defined in an effort to spur research in each area.

It should be noted that the information described in this paper was gathered over the course of a two and a half month effort within the Public Safety Communications Research (PSCR) program of the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Interviews with approximately 20 different firefighters (focus group), based primarily out of the Boulder Fire-Rescue Department (BFRD), were conducted for the purpose of understanding firefighting better, soliciting additional ideas for technology improvement, and capturing feedback on certain technologies. All information and advice gathered from these interviews and from shadowing the focus group (ride alongs) were used to select equipment for investigating some of the technologies listed in this report. The overall cost for equipment, bunker gear, and mannequins to display the information was just under $7,800. Due to the fact that most of the products listed below are not ready for use in actual emergency situations, the research team was able to complete this project at a relatively low-cost. Many of these devices and products need to be outfitted with higher temperature and durability ratings and be modified to meet job standards. Moreover, as it will be explained later, each of these technologies has problems that need to be addressed before proper implementation is possible.

1.1 Background Information

Under the Public Safety Communication Research Program, a joint effort by NIST/CTL (Communications Technology Laboratory) and NTIA/ITS (National Telecommunications and Information Administration/Institute of Telecommunications Sciences), research is ongoing in many facets of next-generation broadband networks for first responders. In view of this research, the program staff requested a brief road map for technology and communications research to support the development of innovative public safety network improvements.

Hence, the project of creating a demonstration of the next-generation first responder was developed. This demonstration will display commercially available technology in ways that provide a proof of concept for different devices and each device's future role in public safety.

1.2 Narrowing the Scope: Firefighters

This initial investigation into potential public safety technology was to be completed in a short three-month time frame. Under that constraint, the focus had to be refined in order for useful results to be obtained. Firefighters were chosen as the primary focus group of the project.

Firefighters face a multitude of situations in day-to-day operations. These include fires, medical calls, search and rescue, and chemical calls. Since the firefighters' scope of work lends itself to situations faced by both police and paramedics, much of the work performed for this paper is applicable and easily transferable to meet the needs of the remaining two groups of first responders.

Throughout the process of investigating technologies for the next-generation firefighter, many local firefighters were interviewed. Specifically, firefighters from two structural stations, the Wildland Fire Management program, and bunker gear research teams, all within the BFRD, were interviewed regarding the technologies discussed above. Lessons learned from our time with the BFRD are incorporated throughout the paper and summarized in Section 4.1.

1.3 Technology Selection Criteria

The investigation into firefighter technology involved internet research, conversations with local firefighters, and ride alongs with local stations, where local refers to the Boulder County area in Colorado, the base for this project. Through the initial research into the state of current technology, a few different devices were selected for further research. These devices provided hands-on experience and were integrated to create a demonstration of the next-generation firefighter. Findings are presented below, with brief descriptions of relevancy.

1.3.1 Situational Awareness

Two main classes of information were considered for firefighter response emergencies. The first class is information delivered to Incident Command (IC). This includes information on all available resources, including individual firefighters. Information such as visuals, locations, and health statistics on each firefighter would be relayed to IC. With such an influx of additional information, the data needs to be displayed in a quickly digestible manner, as there is little idle time in a fire emergency. Incident Commanders are already inundated with vast amounts of information, while needing to make judgments on how to direct units and resources in order to fight and contain the incident. Providing extra information is of little value if it is not presented in an absorbable and effective manner.

The second class of information technology relates to personal protective equipment (PPE) and Health Information delivered directly to the firefighters. This information includes biometrics, hearing protection that would interface with radio communications, and visibility measures. Individual firefighters would also need a device to view information outside of auditory, radio related information. Below lies an initial explanation of some of the technology explored for this project.

As interviews and ride alongs were conducted, much like the distinction between classes of information was found, division among the firefighters became clear as well. Due to the diversity of the landscape in the greater Boulder area, like much of the United States of America, there are both urban and rural areas. Since both areas have their own obstacles and challenges, naturally firefighters in these environments need to adapt their methods. Two types of firefighters were observed: structural and wildland.

As the names suggest, structural firefighters are most apt to deal with urban areas with potential hazards such as building fires, vehicular accidents, and chemical spills. Conversely, wildland firefighters are trained for more rural areas such as mountainous or woodland terrain. To that end, wildland firefighters' skill sets are primarily directed toward fighting forest fires, conducting search and rescue operations, and combating flooding risks. Training for either type of firefighter relates largely to his or her geographical location. Where a firefighter works has a great deal of impact on his or her day-to-day activities. Moreover, the technologies and tools required for the two types of firefighters differ greatly. Some technologies are geared toward use for structural firefighters and may not be feasible for wildland firefighters, or vice versa. The reasons for such limits on the technology are given in more detail throughout the paper.

1.3.2 Selected Technology

The following list serves only to introduce the technology explored in this project. More detailed descriptions of the technologies and their implications will be discussed in the body of the paper.

1. **Unmanned Aircraft Systems**
   By far the most requested piece of technology from every firefighter who provided feedback in the initial focus group, regardless of structural or wildland environment, was unmanned aircraft systems (UAS) technology. Having an eye in the sky that is quickly deployable and can easily communicate with the Incident Command Post (ICP) has huge implications for the amount of information available on scene and the ability to coordinate resources safely throughout a fire emergency. An UAS was acquired during the investigation for hands-on experience and proof of concept for many requested features including live streaming video and Global Positioning System (GPS) tracking.

2. **Body Cameras**
   Body-worn video cameras (body cameras) have been increasingly requested and implemented for police forces in recent years. Applications are available for such devices for structural and wildland firefighters, particularly in devices capable of streaming live

video to both IC and fellow firefighters. Features such as live streaming and direct visuals of points of interest are delivered to IC and firefighters during fires to enable a more informed decision about fire trajectory. Delivering this technology to firefighters may increase the potential for more informed judgments not only to save civilian lives, but also to help manage the incident. No body cameras were available for this project.

3. **GPS Systems**
   In wildland fires, knowing the locations of all firefighters on scene is of critical importance in the mission of keeping fires safe and properly contained. Currently, locations are tracked in the ICP where their locations are marked on a map when firefighters call in their coordinates verbally by radio. This method is slow and rife with potential for inaccuracies. Having models that can update in real time automatically gives firefighters a tool that allows much higher precision and accuracy in positioning themselves to fight a fire. A GPS device was researched for this project and is explained in greater length below.

4. **3D Models**
   Structural firefighters do not have the luxury of GPS systems to track units through fires. Most communication signals, including GPS, are severely attenuated inside of buildings, essentially cutting off firefighters from the outside world. Even in the event that GPS signals are able to breach the walls of buildings, there is currently no accurate method for determining the relative height of a GPS signal from the ground. Implementation of both 3D models of buildings for firefighters to view, and systems of tracking firefighters through buildings, would be invaluable tools for improving the overall safety of individual firefighters. No indoor tracking device was available to the project team, but simple 3D modeling software was evaluated.

5. **Heads-Up Display**
   Getting more information to firefighters on scene in an unobtrusive manner is imperative to the public safety mission. The more pertinent and vital information presented to the firefighter, the more effectively and efficiently the task at hand can be accomplished. The ability to deliver this information decreases the amount of time the firefighters spend in dangerous situations, which in turn decreases the number of injuries and deaths sustained by firefighters as a whole. Finally, improvements in efficiency for handling incidents minimize the cost of damages sustained by home owners, thus benefiting the general population. Overall, the introduction of a robust graphical heads-up display (HUD) system would benefit all individuals involved in fighting fires, and this capability may be a necessary addition for the next-generation first responder toolset.

6. **Biometric Wearables**
   Fighting fires is an incredibly physically demanding occupation, and the health hazards associated with it are immense. The ability to measure the vital statistics of each firefighter passively could improve both the individual's, and IC's, awareness of every firefighter's health and safety. Multiple pieces of wearable technology were considered to measure as many vital statistics as possible with minimal interference.

7. **Hearing Protection**
   Firefighters are constantly in loud noise environments; hence hearing loss is a major concern for most firefighters later in life [4]. To protect firefighters' health without impairing their ability to communicate, hearing protection options that interfaced with communication devices were explored. Multiple variations of similar devices were considered for hands-on experience.

8. **Electroluminescent Tape**
   Maintaining visibility of firefighters is vital, between team members and for retaining exit paths. Current bunker gear visibility in dark conditions is limited to reflective tape sewn to the top coat of the gear. Although use of the tape is practical, other technologies are currently available to improve the brightness of firefighter turnout gear, enabling firefighters to see one another more clearly and in harsher conditions. Several options for reflective materials were evaluated and are presented in Section 3.

2 Strategic Information

Imagine the following two scenarios of wildland and structural firefighters responding to their own respective emergencies.

The call comes in, and dispatch sends the vital information immediately to the wildland firefighters. There is a fire cresting over a nearby ridge and approaching a large population center. Containment is of utmost importance to minimize property damage, and evacuation of the civilian population is ongoing. Immediately, the Incident Commander sends an UAS to gather visual and positional information of the fire. Within minutes, Incident Command has visual images of the fire's boundaries as well as a rough border of the fire represented on a map, generated using coordinates from the UAS's internal GPS unit. The Incident Command Post is able to utilize all available resources efficiently, sending firefighters and planes to the critical points along the fire's path for containment. The UAS is equipped with a thermal imaging camera (TIC), so parts of the fire that appear to be burned out to the naked eye can be identified as hotspots that may flare up again if not handled in a timely manner. As firefighters arrive on scene, the Incident Commander watches their progress in real time on a map complete with each firefighter's GPS location. As one group of firefighters approaches a burning area, the Incident Commander brings up their live video feeds to observe the fire visually. From these feeds, the Incident Commander is better able to coordinate each firefighting unit into safe zones and strategic positions for fighting the fire. With this arsenal of tools readily accessible for use, the fire is contained quickly, responders return to the fire stations safely, and the effect on the surrounding population is minimized.

Another call comes in to dispatch: there is a structural fire downtown. Within two minutes an engine is out of the station, and within six minutes it arrives on scene. However, the responders are not heading into the situation uninformed. On the drive over, the captain received blueprints and 3D models of the burning building and began to understand the building's dynamics. Upon arriving, a firefighter jumps out of the engine and immediately throws a batch of unmanned aircraft vehicles (UAVs) into the building. The UAVs randomly scatter across the first floor and begin pinging each other wirelessly to generate a rough layout of the interior. As the first group of three firefighters crosses the threshold of the building, the now settled UAVs identify each firefighter and report relative locations back to the captain on the computer at the fire truck. Another UAV has been deployed from the truck equipped with a thermal imaging camera, and it is scanning the perimeter of the building looking for any civilians trapped inside. As needed, the captain is able to switch between views from the thermal imaging UAV and the locations of each firefighter, with the capability to pull up live video feeds from each firefighter's body camera. A little while later, the oxygen alert system for one firefighter inside the building sounds to those in the immediate area. Simultaneously, a light illuminates in the individual's self-contained breathing apparatus (SCBA) mask indicating only one-third of the oxygen is left in the tank. Immediately, the captain's computer indicates which firefighter is low on air, how much air is left, and the estimated remaining air time for that particular firefighter based on his or her previous breathing patterns. In response, the captain clicks the "evacuate" button on screen. The three firefighters in the unit, including the low oxygen firefighter, receive a light signal in their SCBA mask indicating the need for evacuation. All three firefighters in the group begin the trek back out of the building and arrive safely outside. Low oxygen tanks are replaced, and the firefighters can regroup before heading back into the building.

2.1 Unmanned Aircraft Systems

When a firefighter is responding to a call, information is vital to the success of the mission. A device that is mobile, such as an UAS, can be used in many different scenarios and altered to fit a diverse range of use cases. Being modular and diverse in its usage, an UAS may be a terrific companion to any first responder with a need for receiving visual data quickly and accurately from a remote location.

2.1.1 Wildland Use Cases

As explained above for the wildland scenario, having accurate information on the fire quickly is imperative to the safety of the wildland firefighters involved, as well as the minimization of damage cost to individuals in the affected area. The ability to use technology to map the perimeter of a fire accurately as soon as possible after a call arrives, allows for quick and accurate deployment of resources to extinguish the fire. Beyond mapping, the ability to obtain visual data through both the visible light and the infrared spectra can be extremely useful when pinpointing the tendencies and hazard zones of the fire as it spreads throughout the forest.

Meeting these expectations requires a device with an attached camera, as well as the capability to integrate a TIC into the system. Such a camera system needs to have the capability to relay live video feedback to a central location where that information can be interpreted and utilized effectively. Also, this camera system needs to be mobile, quickly deployable, and controllable from a distant location. Including these attributes increases the rate at which information can be collected and put into use, meaning the fire can be contained in a quicker and more efficient manner. To that end, the UAS needs to have user-friendly controls. In an atmosphere where firefighters work in shifts of days as opposed to hours, trained specialists may not always be available. Training for such a device needs to be quick and simple, or even better, intuitive to the user during a worst-case scenario.

The UAS needs to be durable and able to withstand the harsh environments of wildfires. A completely fireproof UAS would be helpful, but such an UAS is neither practical nor necessary. Instead, an UAS with some level of fire resistance can be flown outside of extreme temperatures to provide visual feedback for the Incident Command Post.

Finally, the camera system needs to have the ability to gain altitude, ideally above surrounding trees or other natural barriers, throughout the course of the fire. Vertical ascension enables the camera system to view a much larger area, a highly valued feature in wildland fire cases as wildland fires have reached sizes in excess of 550 000 acres, as recorded in 2012 [23]. A bird's-eye view of an incident enables a quicker response, a more effective containment, and safer operations for wildland firefighters. However, with altitude and distance comes the need for a sufficient battery life to sustain the system during flight. Since wildland fires can become quite large, the total flight time, and by extension the battery power, in relation to the weight and powered electronics on board, can quickly become design factors for a practical device.

2.1.2 Structural Use Cases

In structure fire scenarios, there is a need for accurate building and visual information. Firefighters need a device with the ability not only to capture that data, but relay the information properly to the user. In the event of a structural fire, the video relay device should be able to traverse and map the inside of the building dynamically, meaning that the system is capable of exploring and mapping structures without any prior knowledge of style or specific information. Visual ability is generally severely impaired within a burning structure due to smoke, so the UAS must be capable of maneuvering when the human operator lacks visual information.

Additionally, the device should react to a constantly changing environment. Fires are environments that change quickly and drastically, with falling debris and smoke cluttering the limited space within the structure. A combination of precise controls for the human operator coupled with sensors that detect and autonomously react to protrusions and obstacles are imperative for an UAS to be viable in emergency situations.

All information gathered by the device is useless if not relayed to a central location serving as an information source for decisions made by firefighters regarding the strategic plan and attack on fires. Improper information relay can render the device useless to a firefighter, since the device primarily serves as an information probe for the structure, providing IC with unique information critical to the safety of their units.

The device should be able to update a map of the environment in real time, to provide IC with as much pertinent information as possible. Without real-time data, the constantly changing environment of a burning building will render the data sent by the device useless. The device also must be able to survive the harsh conditions of structural fires, mainly high heat and deteriorating buildings.

There are multiple scenarios in which UAS technology would provide useful information to structural firefighters. One such scenario, which occurs more than 366 500 times per year in the United States [6], is a hazardous material spill. For this type of situation, the HAZMAT (hazardous materials) team is called. During these potentially harmful situations, reconnaissance needs to be conducted before any individual physically approaches the problem due to the volatile, and unpredictable, nature of chemical spills. A HAZMAT-operated device would need, first and foremost, to be operated from a remote location. Second, this device would need to have a live video feed for visual assessment of the problem by the user. Third, chemical sensors should support detection of a broad range of hazardous chemicals on the emergency site. With this capability, the HAZMAT team would immediately know what chemicals are involved in the situation and would be better prepared for the repercussions of the reaction. Ideally, the device would be able to relay this information back to the user in real time. Then, the device would need to be able to maintain a robust connection between the transmitter and receiver in the event that the device enters a building. Without this capability, dependability in urban settings would be questionable. Finally, the device would integrate a TIC into its operation in order to identify whether or not the reaction releases heat, which could be a potential source of injury, and be able to relay this data back to IC in real time.

2.1.3 Current State of Technology and Future Endeavors

1. **Wildland Device Solutions and Innovations**
   Using all of the above stated requirements, the next-generation wildland firefighter profile demonstrates the need for an UAS with the ability to stream live video back to the person controlling the device. Beyond live streaming capabilities, the device needs to be able to incorporate a TIC into its arsenal of tools to add effectiveness to its firefighting capabilities. To meet these criteria, the investigation began in commercial industry to look for an UAS with as many of the desired capabilities as possible. After an initial internet investigation, several devices were discovered that met the most of the criteria. Most devices explored were very similar, differing only in camera quality and cost. As all boasted high definition camera quality, the least expensive device was chosen.

   The device evaluated by the project team was fitted with a live video streaming camera that stabilized video feeds via a 3-axis electronic gimbal. The UAS communicated with the controller via a 2.4 GHz radio signal at 0.1 Watts (20 dBm). Four electric motors rotated the four blades that maneuvered the UAS.

   The user controller interface included a GPS tracking trail depicting the UAS's flight path. This flight path was overlaid onto a map with appropriate latitude and longitude lines. There is currently no option for the integration of a TIC, and no indication was

Figure 1: UAS with attached camera.

found that this technology would be available in the near future, as the device lacked the power to lift a device as heavy as a TIC. TIC's are also currently challenging from a cost standpoint.

The battery life of the UAS used during the project was one potential issue, with flight times lasting around 23 minutes maximum. Range was another issue, as the UAS was only capable of transmitting to the controller from a distance of approximately 1.93 kilometers in line-of-sight conditions. Despite the device's initial drawbacks, hands-on impressions were positive. Everything operated as advertised, most notably the operation of the real-time video feed. The video stream was clear, with no stuttering due to connection issues. The 3-axis gimbal also performed incredibly well, with no visible indication of disturbances for the duration of the UAS flight. Overall the UAS is a great proof of concept for wildland firefighters as a cost effective, easily implementable device. Ease of use, high quality video streaming, and GPS tracking are just a few of the features with many implications for wildland firefighting. Once the issues regarding TIC integration, battery life, range, and environmental readiness are acknowledged and improved, such devices may be ready for deployment.

2. **Structural Device Solutions and Innovations**
   Two cases for structural firefighters were examined, resulting in a potential need for two devices to meet the needs of structural firefighters. After conducting initial research, there seemed to be nothing currently available to the public that would meet a substantial number of the requirements posed above. Because of this, research turned to looking at future technologies to identify the gap between where the technology currently is, and where it needs to be in order to be implemented for firefighters.

   Over the course of the initial research, the team discovered a device under development that meets almost all of the requirements laid out for the structural fire scenario. For example, the new system has the ability to create a 3D model of the interior of a room, send this information back to IC in real time, and continuously update its view of the current room, which means it can adapt to the ever changing environment of the burning building. The technology is a swarm of small, low-cost UASs that, in the event of a fire, are released and scatter randomly within the room in question [20]. As the UASs separate, they start to send out infrared light beams and track the distance to each particular wall. Then the UASs combine all their data to create a constantly updating model of the room. Ongoing development work could equip the UASs with sensors that allow them to track firefighters as they move through different floors of a structure. These ideas are discussed more in the *GPS and Tracking* section later in the report. A potential drawback with these UASs is their inability to adapt as well as other prospective devices to environmental hazards such as temperature or falling debris.

There is another technology, however, that better incorporates the idea of object evasion into an UAS. This UAS is based upon the evasive maneuvers found in the fruit fly [9]. If the capabilities of this UAS were merged with those of the UAS previously mentioned, an UAS swarm could be built that meets most of the previously laid out requirements.

After initial research, there seems to be no technology currently available to meet every requirement, but research and development teams are currently working on UAS technology in many of the required areas of advancement. The focus of such research in the field of firefighters needs to acknowledge the issues of survivability of UASs in hostile and ever-changing environments, while maintaining the ability to map rooms and track firefighters as they move through them. The UASs must be able to communicate this information to IC continuously.

The second UAS case pertains to HAZMAT situations, but the UAS requirements differ from those explained in the previous structural use case. Initial research showed that the UAS explored for wildland scenarios could serve as a proof of concept for many of the requirements inherent in HAZMAT responses. However, the UAS did not meet all of the requirements for HAZMAT scenarios, most notably the ability to attach chemical sensors to the UAS. As expected, weight was an issue, as well as a lack of appropriate commercially available chemical sensors, as discussed in a later section. No chemical sensors capable of communicating their information wirelessly to IC in a mobile scenario were discovered in the initial investigation.

For the implementation of UASs to be feasible in HAZMAT situations, the UAS must be able to be outfitted with chemical sensors. Similar feasibility issues exist for wildland use cases, relating to battery life and range factors.

2.2 Live Streaming Video: Body Cams

The more information that can be delivered to the Incident Command Post, the better equipped they are to utilize their resources efficiently and effectively. Incident Commanders interviewed from both the Wildland Fire Division and from stations throughout the city of Boulder at the Boulder Fire-Rescue Department (BFRD) agreed that one of the most impactful pieces of information they could receive would be live streaming video from individual firefighters on the frontline of the situation. In order to be useful, a live streaming body camera (body cam) must meet the following criteria based on the research information gathered:

1. Stream with high enough quality to obtain usable information
2. Low latency in transmission
3. Ability to stream effectively over Wi-Fi/LTE/RF (Radio Frequency)
4. Include GPS/location information with video feed
5. Information presented in a format readily usable by IC
6. Designed to survive a firefighting environment
7. Include location of firefighter when selecting video feed
8. Battery life adequate for both wildland and structural firefighters

This section presents the potential benefits of live streaming body cams for wildland fire departments and structural fire departments, along with some of the pitfalls that still need attention in the realm of body cams.

2.2.1 Wildland Uses Cases

From discussions with the Wildland Fire Management Program within Boulder Fire-Rescue Department, the most iterated point was that in a wildland fire, an Incident Commander must know where all available resources are located. Resources include all firefighters, fire trucks, safe zones, and various other tools and methods for extinguishing fire. The ability to have a real time visual of a firefighter that corresponds to his or her GPS location allows the Incident Commander to understand the call with a more complete perspective. This perspective is a necessity for the IC to coordinate resources as effectively and efficiently as possible. The true benefit of body cams is that they receive information on a scale small enough that they can process details of the fire and situation that can be invaluable in terms of containment and firefighter safety. Viewing a fire's behavior in close proximity from a variety of viewpoints correlated through GPS locations on a map allows the IC to make far better predictions of the fire's trajectory and to allocate resources safely and efficiently. The main pieces of technology that need to be coordinated in order for such a response are as follows:

1. Live streaming body cams on firefighters with GPS capabilities
2. Network/medium for body cams to use for sending video and GPS data
3. Software that allows Incident Commander to process received video data seamlessly and quickly

The current state of such technologies is presented below.

2.2.2 Structural Use Cases

Where a wildland fire can be called a marathon, a structural fire is a sprint. Any information delivered to an Incident Commander must be understood quickly and easily, or IC could be overwhelmed with information. In a structural fire where more (or a more dense concentration of) firefighters would be expected, this kind of overload situation could develop. Following that assumption, the applications for live streaming video via body cams are fewer than in wildland, but they are still rife with potential. In certain emergency situations, visual representations of individual firefighters could be invaluable. In the event that a firefighter goes down, having a device that could give visual identifiers as to his or her location, as well as some sort of location pinpointing through GPS or similar technology, could cut down the time it takes to find and rescue the firefighter. Live stream video feed of the fire can also help structural Incident Commanders understand and predict the future behavior of the fire so that they can coordinate their resources maximizing safety and efficiency for both firefighters and civilians.

2.2.3 Current State of Technology and Future Endeavors

Although the field of live streaming body cameras has begun development, there are not yet many devices available for consumer use, and even fewer are designed or suited for firefighting applications. Though no devices currently on the market meet all the previously mentioned requirements for firefighters, several devices are planned for commercial availability in the coming years that meet at least some of the desired requirements.

Through our initial research into current options for live streaming video, a few key features were found in multiple devices. Many devices were capable of streaming over Wi-Fi, but few were also capable of streaming over 3G or 4G LTE. The more versatile the device is for streaming, the more options researchers have for implementation into a first responder system, as firefighters encounter a range of situations where Wi-Fi will likely be unavailable. As projects like FirstNet develop further and networks become more available for first responders, body camera devices need to be able to utilize those networks.

A few devices also supported the ability to transmit GPS location simultaneously with their live video stream, which is an imperative feature to the firefighting community. Particularly when considering wildland firefighters, the ability to correlate visual information and GPS locations furthers an Incident Commander's ability to analyze and prepare for a situation while keeping firefighters as safe as possible.

Another key feature worth mentioning is that some software systems allow an authorized user to monitor multiple devices simultaneously in a way that is clear and simple. The footage being captured has to be processed by someone on scene, and in an emergency situation the easier the information is to understand, the greater the chance that firefighters will be able to use it. The simplicity of the system is paramount to the utilization and effectiveness of the system.

Finally, a body cam, as with any device incorporated into a firefighter's uniform, must be durable. The conditions of a fire are extreme, and firefighters' equipment is seldom in a protected environment. The firefighter may come into contact with extreme heat, water, mud, and thick foliage, depending on the emergency. Thus, a camera must be able to survive these elements without impairment to its ability to gather or transmit data.

Due to the fact that many of the devices researched are, so far, unavailable to purchase, obtaining a device for hands-on impressions was not possible. However, the main areas we identified from our initial research in which current technologies are not yet feasible, are unable to meet the needs of firefighters, or require policy debate and implementation are as follows:

1. **Readability of Information**
   A significant influx of information critical to firefighting comes to the Incident Commander during a fire emergency, whether it is a wildland or structural incident. Often there is little time to make decisions and consider options, so it is absolutely critical that any extra information delivered to the Incident Command Post is easy to digest. In the case of live streaming videos, having a visual layout that allows the Incident Commander both to track firefighters in the building and to select individuals to receive their video feeds seamlessly is imperative. At this time, tracking firefighters through a structural fire is a major technological hurdle as GPS-based systems fail inside of buildings. This idea is discussed further in Section 2.3.2.

2. **Durability**
   Most firefighters, by nature of the job, are very rough on their equipment. The equipment must be able to survive not only the incredibly harsh environments encountered inside of fires, but also the realities of gear transportation in the fire service. A piece of technology is only as useful as it is durable, because when on duty, firefighters do not have time to keep track of and maintain fragile items. Delicate equipment, no matter how useful, will be abandoned and forgotten if it is not robust.

3. **Battery Life and Weight**
   When utilized to support a structural fire incident, ideally all electronic components would be powered by one battery within the SCBA unit to simplify preparation for the firefighter. This means that the body cams would have to be able to coordinate their battery needs with those of the SCBA units, without drawing too much power and causing reductions in the battery life of all other connected devices.

   For wildland firefighters, batteries are a major issue, with some firefighters carrying upwards of 50 AA batteries when going into the field. A battery for a wildland firefighter must be replaceable, universally usable across devices, and hold a sufficient charge for the devices powered by the battery.

4. **Database Management**
   As police departments around the country have discovered when attempting to implement body cameras, the cost of storage can grow very quickly. Many police executives

agree that data storage is the most expensive part of body cam programs [14]. As fire departments attempt to implement their own body camera programs, they will face the same costs and be required to make decisions appropriately for their organizations. Conversations with leadership in the Boulder Fire-Rescue Department confirmed that footage generated from a body camera program could be vital in the analysis of fires, particularly as evidence in the investigation of arson cases. As such, the footage would need to be stored appropriately so that it could be referenced as needed in the future.

5. **Freedom of Privacy**
   Depending on state laws, footage recorded by a fire department may be available for public access under acts such as the Colorado Open Records Act (CORA) [3] and the California Public Records Act (CPRA) [2]. When responding to a fire, department personnel may generate public record footage of the inside of personal dwellings as well as commercial businesses. Some sort of policy implementation would be required in order to protect individual rights to privacy, as it may not be feasible to have individuals consent to allow firefighters to utilize body cameras when responding to fires at their personal dwellings or businesses.

2.3 GPS and Tracking

When a unit is on the site of a fire emergency, knowing the positions of all firefighters is critical. As situations develop or firefighters go down, the ability to locate a unit, or an individual firefighter, quickly reduces risk of injury and death. Information delivery must be prompt, accurate, and readable. In this section, use cases for wildland and structural firefighters, the current state of technology, and work to be developed for the future will be discussed.

2.3.1 Wildland Use Cases

An Incident Commander engaging a wildland fire must be able to get each unit out of dangerous situations quickly. IC also must be able to coordinate units together towards strategic points in the containment of the fire. To do this, IC must track the general positions of all firefighters. Currently, tracking is accomplished by verbal radio reports of latitude and longitude coordinates from firefighters to IC. This is clearly a time-consuming and error-prone method. Through the initial investigation into GPS and tracking technology, as well as using the "10 Standard Firefighting Orders" and "18 Watchouts Situations" defined by the National Forest Service (NFS) [21], the following criteria were developed for use cases for wildland firefighters:

1. **Map of Area**
   As a general requirement, all location data for firefighting resources must be correlated to and presented on a geographical map of the incident and surrounding areas.

2. **Topography**
   Knowing elevation changes and topography of the affected area helps immensely in both planning trajectories of the fire, as well as planning appropriate safety zones and

escape routes. Particularly for units who are unfamiliar with the terrain in the area where they are working, topographical maps become imperative, as firefighters must avoid entering any area without a quick and clear exit strategy.

3. **Locations of other firefighters**
   In order to locate other firefighters, each individual must be able to see all other firefighters' positions on the map mentioned above. Simply showing direction and distance to other firefighters may be an acceptable alternative to a map.

4. **Information Delivered to Incident Command**
   In order to direct different units of firefighters and allocate resources appropriately, Incident Commanders must know the real-time, relative positions of all resources, including firefighters, to problematic terrain, and safe exits paths.

5. **Push/Receive Waypoints**
   Having safe zones, escape routes, strategic points, and fire boundaries marked on a map that is accessible and editable to both Incident Command and individual firefighters increases the overall situational awareness of the team. Availability of this information improves unit safety, fire containment, and incident management.

6. **Fire Weather Conditions & Forecasts**
   Events such as the Yarnell Hill Fire demonstrate the incredible impact that weather conditions can have on a fire's intensity and trajectory. In that event, with the arrival of a thunderstorm, the fire spread changed direction, speed, and size, overwhelming and killing 19 firefighters [24]. Knowing the weather conditions and forecasts gives firefighters and Incident Commanders more information about potential risks in the fire to keep crews and civilian populations safe.

7. **Field Rechargeable**
   Many wildland firefighters carry more than 50 AA batteries and use upwards of 20 batteries per day. Having a device that is capable of being recharged quickly in the field is a vast improvement in terms of minimizing weight to the firefighters' already heavy loads.

The current state of tracking technologies available to wildland firefighters will be discussed in a later section.

2.3.2 Structural Use Cases

There is no method currently in use for tracking firefighters through structures. GPS does not function reliably inside buildings, and firefighters are not equipped with any location devices except simple alarms that emit loud noises in the event that a firefighter is injured or incapacitated. Through the initial investigation into tracking technologies, the following criteria were developed for tracking technology in structural fires:

1. **Functional Inside Buildings**
   In order for location tracking to be useful, it must function inside firefighting environments. GPS reception fails consistently in buildings and is therefore not viable unless it is heavily augmented.

2. **Reasonably High Precision and Accuracy**
In order for the information to be useful for structural firefighters, displayed locations must be as precise and accurate as possible with current technology solutions. A displacement between actual and predicted positions of even 6 meters can be significant when trying to locate a firefighter in an emergency situation.

3. **Master List of Locations for Each Firefighter**
For firefighters to be able to locate each other in an emergency, they must be able to see either relative positions or a direction and distance approximation for all firefighters on scene.

4. **Information Delivered to Incident Command**
Using the same rationale applied above for the wildland scenario, it is clear that Incident Commanders of structural firefighters must know the relative positions of all available resources in real time to direct each unit properly and allocate supplies correctly.

5. **Needs to Differentiate Floors**
Tracking technology in a building is not useful unless it is able to distinguish locations reliably in the vertical direction (e.g., between floors in the building). If a device reports the wrong floor for a firefighter who needs rescue, the rescue teams may waste resources and endanger themselves in a rescue attempt directly above or below an injured firefighter.

2.3.3 Current State of Technology and Future Endeavors

Currently, there are quite a few devices on the market which enable GPS tracking for wildland firefighters. We found no tracking devices developed commercially for structural fires, but some technologies currently in development could serve structural firefighters' purpose well.

1. **Technology Available for Wildland Firefighters and Work for the Future**
Many devices are currently available that provide the ability to deliver live position tracking. These devices come in the form of wearables (e.g. smart watches, HUD), android devices, or standalone GPS devices. Many of these devices also meet most of the requirements stated above in the Wildland Use Cases section. Table 1 details a series of explored devices and available features including wearables, GPS, Global Orbiting Navigation Satellite System (GLONASS), Topography (TOPO) capabilities, camera capabilities, weather data, Biometric (BM) information, and Remote Monitoring Software (RMS).

   Inclusion of remote monitoring software with a device is a huge advantage, as it simulates the experience that an Incident Commander might have with the technology. Devices 1 and 5 were the only devices with that feature included, so both were researched. Device 1's inclusion of weather information, in addition to the fact that it met more of the aforementioned requirements than any other device, led to our focus during hands-on research.

Table 1: Features of Potential Position Tracking Devices

Device	**Wearable**	**GPS**	**GLONASS**	**TOPO**	**Camera**	**Weather Data**	**BM**	**RMS**
Device 1		X	X	X	X	X		X
Device 2	X	X					X	
Device 3	X	X	X	X				
Device 4		X	X	X	X			
Device 5		X						X
Device 6	X	X			X		X	

Communications technology support was also considered in the selection process for tracking devices, keeping in mind the proof of concept demonstrations which would be required for the program. Family Radio Service (FRS) and LTE were the two mediums that were valued most primarily due to their current and planned utilization for first responders. The reader is directed to [5] for an overview of FRS. No commercially available device was found offering location technology over LTE communication. However, Device 1 was capable of FRS communication as shown in Table 2 below. The table also illustrates other potential modes of communication for the devices including Wi-Fi, Bluetooth, Near Field Communication (NFC), and Family Radio Service/General Mobile Radio Service (FRS/GMRS) connections.

Table 2: Types of Communication Abilities for Select Tracking Devices

Device	**Wi-Fi**	**Bluetooth**	**NFC**	**FRS/GMRS**
Device 1				X
Device 2	X	X		
Device 3	X			
Device 4	X	X	X	
Device 5				X
Device 6	X	X		

Power options were also considered for each device. As indicated by Table 3, all devices explored had rechargeable lithium ion batteries, but only two had the option to replace the lithium ion batteries with AA batteries if needed. Since wildland firefighters already carry batteries, the fact that the backup power option of Device 1 was compatible with those batteries led to focused research during the hands-on portion of the project.

Hands-On Testing Experience

A few of the most requested features from conversations with wildland firefighters were investigated, using Device 1. The ability to view other firefighters on a map and get

Table 3: Tracking Device Battery Types

Device	AA	Rechargeable Lithium Ion
Device 1	X	X
Device 2		X
Device 3		X
Device 4	X	X
Device 5		X
Device 6		X

position updates worked very well on this device. A concern with the technology was that the positioning did not update constantly, but instead only when the device was polled by another location device or Incident Command itself. This means the only ways to update each device's location are via waypoint reception, or manually polling another device. One drawback of this method is the limit on how often a device can be polled. Each device is only able to send poll requests, waypoints, and location information once per minute. Although this method maximizes battery life, limiting how often each device can poll other devices is not ideal for quick-paced firefighting situations. Despite these concerns, this system of polling still vastly outperforms the firefighters' current methods of recording location by radioing in longitude and latitude coordinates to be jotted down on a map.

Figure 2: Position Tracking Device 1.

Some features of the device that stood out as particularly useful were the ability to project and share waypoints with other users, as well as the ability to view and follow other users' tracks on the map. Although not experienced, the need for topographical maps was also apparent. It would be difficult to identify and send landmarks accurately without topographical maps.

Finally, the implementation of National Oceanic and Atmospheric Administration

(NOAA) radio weather reports worked well. This could prove invaluable in saving firefighter lives in the line of duty since local weather patterns and forecasts can be quickly requested and read over the radio.

Device 6 was also researched for the initial investigation into tracking technology as it incorporated the unique feature of a heads-up display (HUD), which will be discussed further in a later section. Device 6 had a “find my friends” feature that allowed users to add each other through a computer or mobile-based application, then locate and track one another using the device. There were two different methods for using GPS on Device 6: a compass showing direction and distance to friends using similar devices, and a map of the area with locations of friends plotted on it.

Through the initial exploration of this technology, several issues were discovered. First, as expected, the device performed poorly inside or near buildings, with errors in location approaching 15 meters or more, and errors in direction as high as 180 degrees. Outside, the device performed better, and many of the issues regarding incorrect distance and direction measurements were minimized, but certainly not eliminated.

Device 6 did seem to rely predominantly on the Bluetooth-connected smartphone for its GPS location, despite the fact that the device had its own GPS built in. This was a drawback, as the smartphone application required an LTE or Wi-Fi connection to work, limiting the scope of use for the device for no discernible reason.

Overall, Device 6 demonstrated proof of concept for GPS use cases for wildland firefighters. However, the device is not likely a viable solution for reasons detailed in the *Heads-Up Display* section of this report.

From the initial exploration of available GPS and tracking technology for wildland firefighters, it was found that there are pieces of technology available today that could be integrated into wildland firefighters’ gear fairly seamlessly. These devices can not only directly replace existing GPS units, but they also introduce additional features. The ability to mark, send, and receive waypoints, locations, and tracks from other firefighters and the Incident Command Post, as well as receive weather information, could prove invaluable to wildland firefighters. The main points of concern for integration of these types of devices are cost, battery life, and accuracy.

2. **Technology Available for Structural Firefighters and Work for the Future**
Currently, firefighters receive two-dimensional building layouts from dispatch via a built-in fire truck laptop while en route to a fire. Unfortunately, only a small percentage of building layouts are available, and of those, many are not up to date. Furthermore, the layouts database must be maintained and updated by firefighters, a time consuming and impractical task. Beyond receiving building layouts, firefighters requested an indoor personnel tracking overlay for the building. However, there is currently no commercially available technology for accurately tracking firefighters through a structure during a structural fire. Radio frequencies, such as GPS, do not propagate

well through walls and ceilings in buildings. Therefore, different technologies must be developed that allow firefighters to be tracked through a building, with the imperative feature being differentiation between floors of a building. There are quite a few groups working on this problem today. Below is a list of methods we studied, as well as potential suggestions generated from discussions with firefighters.

(a) **Standalone Tracking System**
One product currently in development not only tracks personnel through a building, but also generates a map of the building as the subjects move throughout the space. All generated information is delivered to a command center application to create an interactive building model with live personnel locations. As individuals move through indoor spaces, embedded device sensors on each person use radio frequency features and signatures to form indoor navigation maps. These maps contain building structural features such as hallways, elevators, exits, and stairwells. The software creates not only two-dimensional mappings of floors, but generates three-dimensional mappings of the entire building, allowing personnel to be tracked floor to floor.

(b) **Position Tracking in Pre-Existing Emergency Systems**
The Occupational Safety and Health Administration (OSHA) requires all commercial buildings to have clearly marked exits and emergency signs in every room [13]. Also, there are almost always emergency lights and fire alarms in every room. Utilizing all these resources together and embedding each one with sensor chips, one could generate maps of rooms that track first responders' movements through each room. Although this idea is feasible using existing standards of such technology, the cost of upgrading all mentioned devices in every building in a city, or across the nation, would be significant. Furthermore, there may be inherent problems which would prevent positioning of all such devices cohesively to construct accurate tracking maps.

(c) **Unmanned Aircraft Vehicles that Map and Track (Carnegie-Mellon)**
As discussed in the above section on UAS technology, there are research groups developing mobile systems of low-cost deployable unmanned aircraft vehicles (UAVs) that pseudorandomly scatter around rooms and generate a network together to map and track firefighters' locations as the individuals move about the building [20]. This solution for dynamic room mapping and tracking has many benefits. First, unlike other systems for tracking that would rely on universal standardized implementation of sensors in all buildings, an incredibly high cost venture, this system would be low-cost, adaptable, and functional in any situation or building structure. There is no real cost of maintenance, and the primary point of failure relates to the fire department's vigilance in checking the gear to ensure functionality of the system. In contrast to the low-cost UAV system, for other networks where the tracking equipment is preinstalled, in the event of an emergency the sensors may become damaged or destroyed. Thus, vast amounts of redundancy would be necessary, increasing cost without guaranteeing functionality. The low-cost UAV method described here has redundancy inherent in its

design. Feasibility of this approach is supported by recent technology advances in avoidance and collision detection in emergency situations such as fires [9][25].

3 Health Information and Awareness

Personal protective equipment is vital to every firefighter's survival. Firefighters presently use devices such as self-contained breathing apparatus, bunker gear, and face masks for protection in potentially harmful situations. Although this equipment is effective, firefighter safety may be vastly improved by adding capabilities to these devices. Improvements and additions such as biometric and chemical sensor readouts, hearing protection, cooling material inside the turnout gear, and brighter luminescent material for the outside of the turnout gear can push firefighters to the next level of protection, health awareness, and comfort. The implementation of some of these tools can be applied to current SCBA units or a futuristic HUD for ease of access. Ultimately, the realm of personal protective equipment has plenty of areas in need of improvement for the sake of the health and safety of firefighters.

3.1 Heads-Up Display

As time goes on, bringing technology into the next generation increasingly incorporates the Internet of Things. The more data that can be displayed in a compact and intuitive form, the higher the chance of success, and the more informed someone can be on any given task. As this sort of technology reaches greater degrees of feasibility, it becomes of greater importance to incorporate it into the next-generation first responder.

3.1.1 Wildland Use Cases

In order for the heads-up display (HUD) to be acceptable for use by the next-generation first responder, there are a variety of requirements that need to be met. First and foremost, the HUD needs to be built into the technology that wildland firefighters are currently using. Because a firefighting activity often spans several days, sun protective eyewear is an important part of the personal protective equipment of a wildland firefighter. Unless the HUD is integrated directly into eyewear that is compatible with existing equipment the firefighters are using, there will not be enough benefits from a HUD to merit its use. The HUD must be able to draw information from external sensors. HUDs may be used to keep users informed with all the information that is currently available to them, as well as inform them as to the status of their surroundings and the conditions of their bodies. If a device is unable to draw information from other sensors (for example, the t-shirt described in the *Biometrics* section of this report), the user will be constrained to the capabilities of the headset on its own, severely limiting the information output of the device. Also, one of the main problems of eyewear pertaining to wildland firefighters is the fact that the current technology is disposable. As one example, eyewear may be covered in tree sap during cutting and containment operations, necessitating the disposal of the eyewear after each incident. In order for the HUD technology to be feasible, a workaround will be needed. One possible fix would lie in making the device modular, so that the eyewear itself can be replaced while keeping the associated electronics. Alternatively, research might be conducted with a goal for making the eyewear immune to the effects of tree sap which beset the current technology.

Along with the idea that the eyewear will need to be immune to the effects of tree sap, more generally, the device will have to be robust enough to handle daily use in the extreme environments of wildland firefighters. If the device is able to incorporate all the requirements listed here, it should be feasible for use by wildland firefighters. Ideally, the device would also be able to interface well into a network with other firefighters and the Incident Command Post. The ability to push images, videos, positions on maps, and other information within this network could be critical for quick and safe containment of fires. Finally, the device should be able to integrate a thermal imaging camera into its optics (and stream this video to IC, as required for the normal optics), allowing the wildland firefighters to view embers that could possibly start another branch of fire from the main burn. This TIC would have to be capable of detecting an ember floating through the air, and be portable enough to be incorporated into the HUD experience of the firefighter. All of these requirements should eventually culminate in a pair of sunglasses that displays location information, communication information, and possibly biometric data, while sharing this information with other individuals in the unit. As the demands of the next-generation firefighter evolve, we expect to see a growing list of accessories to integrate with the HUD.

3.1.2 Structural Use Cases

Structural firefighters have their own set of requirements for a HUD, unique from those of wildland firefighters. Wildland and structural firefighters present the same needs, for example, when discussing the ability of the device to draw in information from external sensors, or the inclusion of a TIC into the device. Those external sensors may vary with application, but the necessity of compiling information from other devices remains intact. From here, though, the requirements become specific to each firefighting scenario.

With structural firefighters, the HUD device must be integrated into the SCBA mask or visor of the firefighter's equipment. Otherwise, a large number of complications could arise and cause the device to become impracticable, and impractical, very quickly. If the HUD is not directly integrated into the mask of the firefighter, it will impair vision, which is already limited significantly in a structural fire. Having the HUD built into the mask also cuts down on the amount of gear that firefighters have to track when going to a fire. There is no chance of misplacing or forgetting the gear when it is integrated fully with an SCBA unit. Next, the HUD needs to have intuitive user controls which would be easily operable during the event of a structural fire. Firefighters wear bulky gloves when responding to a fire, thus operation of technology may become cumbersome. Additionally, during a fire, firefighters often are searching for victims, using tools (such as axes), or controlling a fire hose which renders them unable to control a HUD with small intricacies. Ultimately, without easily operable controls, the HUD would be useless to a firefighter in full bunker gear. The information might be available, but without the ability to navigate to different pieces of information, the HUD would be more of a hindrance than an advantage. Also, the HUD needs to be able to convey information in a way that informs the user but does not interfere with the firefighter's work. For example, the HUD would not fit this requirement if it popped up information regarding the surroundings of the firefighter but displayed the information in a way that impaired the firefighter's vision. Because the firefighter could not see through the display, it would hinder the firefighter's ability to do the job at hand. Finally, the HUD needs to be rugged and robust enough to handle everyday use by structural firefighters. If the HUD breaks or becomes unreliable due to physical stability issues, it will not be feasible to put it into use.

3.1.3 Current State of Technology and Future Endeavors

Initial research yielded many different device options for hands-on experience with the technology. In the end, the options were narrowed down to two devices. These two devices were initially picked over all the other competitors because of their relevance to the requirements listed above. The primary problem which eliminated devices from consideration was a lack of robustness of the technology, along with initial internet research yielding questionable reviews about each device's respective method for projecting the image to the user. Both of the chosen devices were related to smart glasses, which are a group of devices that have small computers placed upon a pair of glasses or sunglasses, projecting an image in various ways to convey information to the user. Because research indicated that there are no current graphical HUD technologies incorporated into the visor or mask of structural firefighters, it was decided that the HUD technology chosen would not meet the requirements presented above for structural firefighters. There are in fact some devices available which use simple light emitting diode (LED) displays in their masks, and those are discussed in following sections.

There were no devices found capable of overcoming the tree sap problem for wildland firefighters, which remains as an ongoing requirement for future devices. It should also be noted that there is currently no technology commercially available to incorporate a TIC into a heads-up display in the manner that is described above. Ultimately, all these requirements, from all technologies, should come together to display pertinent information on the screen of a HUD. Information would include biometric data, air tank pressure, location of other firefighters, communication feeds, and building layouts–anything that would further the cause of informing the firefighter to create a safe and efficient environment. Our evaluation of the chosen display devices is summarized for both scenarios in the following paragraphs.

1. **Wildland Devices**
   The two devices primarily explored both incorporated the idea of attaching a computer to a pair of glasses, but they use different methods for projecting the image to the user. The first pair projected the image onto the glasses in front of the user with a very small projector, whereas the second pair projected the image using a small onboard screen located on the bottom right-hand portion of the glasses (note that this second device is the same as Device 6 in the *GPS and Tracking* section of this report). Because the first device used projection of a screen instead of providing a small screen on the device, it was perceived more as an augmented reality experience than the second device, which simply displayed the information via a physical screen. Concerning physical

design, there was a significant difference between the two devices. The first device incorporated a more progressive and "in style" pair of sunglasses to contain its computer, whereas the second device went with more of a "sporty and rugged" style (see Figure 3).

Figure 3: Device 6: GPS and HUD device.

The processing power and screen resolution for these devices were too close to differentiate, therefore the device selection was based upon the type of projection used and the style of the device. In the end, it was concluded that the second device best fit the requirements for the wildland firefighter. This was due to its ability to incorporate data from various biometric sensors, which met the requirements listed above. After initial internet research, it was concluded that the first device did not have that ability, and hence it would not be able to give any information to the user other than the information provided by the device itself. That constraint limits the use of the first device significantly and hinders any future modifications to develop the device.

Furthermore, the technology incorporated into the physical screen on the second device seemed more robust than the projection technology incorporated into the first device. This is due to the fact the projection technology of the second device was not necessarily meant simply to display information, but to have the user interact with it and to overlay the information over the view of the user. Such an overlay may hinder the user's view of reality; the user may not be able to look past the overlay to see something directly in front of him or her. This could be a major problem for firefighters as their main goal is to traverse an already less-than-ideal area with a limited range of view. The second device incorporated a simple physical screen which would simply inform the user of important information without projecting it into the "world" of the user. This method of projecting information is more feasible for the wildland application because none of the information would be more useful if overlaid onto the user's environment. Finally, internet research indicated that the second device is more durable than the first device because it was designed to be used by athletes. It had features such as built in compatibility with biometric measurements, water resistance and a more rugged design, and those characteristics made it a better match for the expected working environment than the "stylish" design of the first device. Thus, the second device, as stated in the *GPS and Tracking* section of this report, was selected for hands-on experience.

Any future HUD device vendor must, first and foremost, integrate a TIC into its user interface, as well as integrate the entire system into the sunglasses of the user. Without thermal imaging ability, the HUD technology may not be feasible for use in the field. Initial research concluded that there is no technology currently available that meets these requirements, and our work confirmed that advancements are needed for developing commercial HUDs for deployment in the first responder community. Also, with respect to the TIC, there is currently no technology small enough or accurate enough to be suitable for wildland firefighters. TICs need to be lighter in weight, cheaper in price, and smaller electronically for full integration into a HUD. Moreover, TIC technology needs to advance significantly before public safety in general will be able to take advantage of the technology.

2. **Structural Devices**
   On many current Self-Contained Breathing Apparatus units there are primitive HUDs built into the sides of the mask. These are not graphical HUDs, but they accomplish their function using simple arrays of LED lights. A common example of such a mask has air tank pressure represented by four multi-colored LEDs on the right side of the mask. Four green lights represent a full tank, three green lights represent a 75% full tank, two yellow lights represents 50%, and one flashing red light represents 33% tank pressure, which signals the user to leave the structure and refill air. On the other side of the mask there is an assortment of lights representing everything from dangerous temperature warnings and evacuate icons to inter-device connectivity status (Bluetooth, etc.). The LED arrays allow firefighters to be informed on some important vital statistics, have visual warnings of danger, and be generally better informed in an unobtrusive manner. Though the information that can be displayed on such a HUD device is certainly useful, the applications possible with a full graphics-based HUD could serve the next-generation firefighter well.

   With respect to the structural firefighting graphical HUD device, initial internet research concluded that the same device requirements applied to structural and wildland firefighters. The first device still retains all the pros and cons from the wildland firefighting section, and the same goes for device two (again, this is the same device as Device 6 from the GPS and Tracking section of this report). Using the requirements listed above, it was found again that device two is the better option for structural firefighters. With its optical trackpad, it is usable while wearing gloves in a structural fire situation, which is an important requirement for accessing information. The first device does not offer as many on-board buttons as the second device, as it contains only simple volume and select controls. This was one of the important distinctions between devices for structural and wildland firefighters.

   Initial hands-on impressions of the second device were positive. The technology works well, but unfortunately, the small screen obstructs the bottom-right portion of the user's view. The selection of supported sensors is not as wide as would be needed for this device. The screen of the device works well; it projects the correct information, and the quality is high enough that the information can be read easily. The product seems to be durable enough for recreational and athletic applications, but a more robust purpose-built technology should be incorporated before the device is used in firefighting situations. Concerning further innovation, more work is needed to make this technology feasible for structural firefighters than for wildland, due to the intensity and conditions of the structural firefighting environment. While each scenario requires unique innovation areas, in general, current generation technology for HUDs requires advancement before it can be implemented.

3.2 Biometrics and Health Information Sent to Incident Command

Personal protective equipment is one of the most important assets of a firefighter; as such, PPE is an important area to investigate when creating the next-generation first responder. PPE is vital to the next-generation firefighter, because it is the first line of defense for firefighter safety in hazardous situations. In the same way, keeping up-to-date information on the vital statistics of firefighters will help to keep firefighters safe and aware when they are presented with hazardous situations, potentially out of range of colleagues.

3.2.1 Use Cases

During a structural or wildland fire incident, there are many potential hazards to the firefighter, apart from the fire itself. Approximately 59.6% of all firefighter deaths from 2004 to 2013 were caused by overexertion or stress [7]. This statistic underscores the importance of close monitoring of the vital statistics when outfitting the next-generation firefighter.

Our initial research found that the most important statistics to monitor during an event would be vital signs: heart rate, blood pressure (BP), respiration rate, and body temperature. A device with the ability to measure and record these statistics accurately is the most important requirement. Beyond this capability, the device must be able to transmit this data back to IC in real time. The effectiveness of the data is greatly reduced if it is not available in real time during the event. Constant monitoring of biometrics during the event would improve the safety of all firefighters involved. Also, the connection between the firefighter and IC must be robust enough to transmit through structures, and over long distances without fail; otherwise, it would not be reliable enough for implementation. Ideally, the device would also be able to give users awareness of their own vital statistics as they are reported back to Incident Command; having two tiers of awareness for each firefighter's health gives the best possible chance of maximizing firefighter health and safety. Finally, the device must be able to record all these statistics passively. "Passively" in this context means that the device should not interfere with the general operations of the working firefighter. Invasive sensors would make integration difficult–inhibiting the firefighters' ability to work at full capacity can be potentially hazardous and would lead to low adoption rates among firefighters and departments.

3.2.2 Current State of Technology and Future Endeavors

The current consumer technologies available for acquiring an individual's heart rate, blood pressure, respiration rate, and body temperature are detailed below.

1. **Heart Rate Monitoring**
   After conducting initial internet research, it was concluded that there is no one commercially available device that fits all the criteria listed above. The goal was adapted to measure the highest number of vital statistics with the fewest number of devices worn by the firefighter.

   In the effort to identify the optimal set of devices for research, the project team found that two methods were used to monitor heart rate. The first method uses a green LED pulsing at a high frequency, which is typically incorporated into a watch worn on the wrist. The second method uses a chest strap device.

   For the first method, the light emitted from the LED is reflected by the blood in the blood stream, and the reflection is translated into a heart rate reading. This method for reading heart rates is passive; constant strobing of the green LED on a wrist-worn device does not in any way inhibit the firefighter's performance. There is a drawback, however. When monitoring heart rate using an LED, the accuracy of the heart rate reading tends to decrease when the person being monitored is constantly increasing and decreasing his or her heart rate in a short time frame. This is due to the fact that the way the LED measures heart rate does not allow it to follow extreme rate of change in heart rate. In a firefighter's line of work, heart rate changes may be drastic and frequent. Without an accurate heart rate measurement, especially near peak rates, the viability of a wrist-worn heart rate monitor decreases drastically.

   

   Figure 4: Wrist-worn heart rate monitor.

   When using a chest strap, the positives and negatives are actually opposite from those of the LED heart rate monitor. The chest strap heart rate monitor is much more accurate than the LED heart rate monitor, especially during peak activity levels. This point was initially indicated by a number of online reviews and in conversations with users in the fitness community and was confirmed by the research team while using both devices simultaneously. Most of the performance advantage of the chest strap seemed to come from its ability to record higher rates of change to a much greater degree of accuracy. This means the chest strap can be much more accurate for the application, sensing when the heart rate of a firefighter reaches peak levels and becomes potentially hazardous. The downside of the chest strap is that it not nearly as passive as the wrist-worn LED monitor. The chest strap is an elastic band wrapped around the chest of the user, which means that it can potentially lead to the restriction of chest movements. The chest strap also needs to be worn with direct skin contact, under all layers of clothing. It is impractical to think firefighters would wear the strap constantly when on call; however, it is even more impractical for them to put on the device in an emergency situation, wasting valuable time and risking lives of potential fire victims. Despite the challenge in deployment, the chest strap would provide accurate information (unlike the LED solution).

In the end, initial research concluded that the chest heart rate monitor led to a more successful heart rate monitoring device. First impressions of heart rate monitors were conducted on a heart-rate chest strap integrated into a t-shirt; an LED monitor was also acquired for comparison. Attempting to minimize the number of devices worn by the firefighter while still receiving the maximum amount of vital data, the decision was made to purchase a device that incorporated both a heart rate chest strap and a respiration chest strap into one t-shirt. Hands-on experience with this device has proved that it functions as well as expected. The device seems to be comfortable enough to merit use on a regular basis, and the data provided seems to be accurate, as it records spikes during physical exertion. The respiration rate aspect of the t-shirt will be discussed in the *Respiration Rate Monitoring* section of this report below. In order to make this t-shirt device more feasible in the future, the device should implement the ability to measure skin temperature as well as blood pressure. Further information on this subject appears below as skin temperature and respiration rate are discussed in depth.

2. **Blood Pressure Monitoring**
The second vital statistic explored was blood pressure. In general, blood pressure is measured using a device that momentarily restricts blood flow in the arm, and then notes the pressure at which the heartbeats of the patient are still heard through a stethoscope [22]. Blood pressure is recorded as the systolic blood pressure over the diastolic blood pressure [22]. The diastolic blood pressure measures the pressure in the arteries between heartbeats [22].

Outside of very advanced hospital equipment, research showed that there is currently no way to monitor the blood pressure of the user passively. The hindrance caused by restricting the blood flow in a firefighter's arm at regular intervals could prove life-threatening. We found that blood pressure is a difficult statistic to monitor on a firefighter during an incident. The systolic blood pressure measures the pressure in the arteries when the heart beats [22].

3. **Respiration Rate Monitoring**
   Next, initial research was conducted on respiration rate. The research concluded that, beyond experimental equipment, the only way passively to monitor the respiration rate of a user is through the use of a band, not unlike the one used to measure heart rate [10]. The band is placed around the chest of the user, which expands and contracts along with his or her breathing. The device then interprets these expansions and contractions of the elastic and records them into concurrent respirations. This method seems to be very accurate for reading respiration, as there is a very strong relationship between respiration, and expansions and contractions of the user's chest. The method is fairly passive but suffers from the same problem as the chest-mounted heart rate monitor in that it slightly restricts the movement of the user's chest and must be worn under any other layers of the user's clothing. Aside from these drawbacks, the chest strap respiration rate monitor fits all achievable monitoring requirements laid out above.

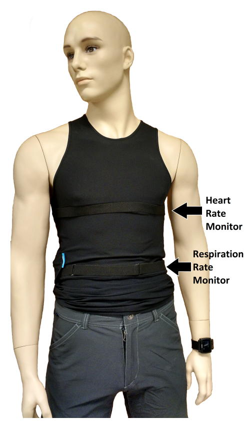

Figure 5: Usage of the respiratory rate monitor is illustrated by the bottom band shown on the mannequin. The top band indicates the heart rate monitor described in *Item 1* of *Heart Rate Monitoring* of this section.

As introduced above, the device considered by the project team was a t-shirt with integrated sensors for both heart rate and respiration rate. The respiration aspect of this shirt worked as advertised. Under initial use, the elastic band sensor appeared to respond at a very consistent rate with respect to chest expansions and contractions, indicating that the strap was reasonably accurate. In its current state, this sensor seems to be able to complete all the requirements laid out above, as the shirt itself is Bluetooth enabled and connects with a smartphone. Thus, the device as designed should be capable of transmitting the individual's data to both the Incident Command

Post and the user. In the initial hands-on experience, the capabilities of the device were not examined beyond simple transmission to a smartphone via Bluetooth. For full integration into firefighter PPE, the device would need to be developed in a way that the data could be relayed to Incident Command in a readable format. Further, the relay device would need to be able to communicate long distances and through walls in structures.

4. **Body Temperature Monitoring**
   Finally, body temperature monitoring was explored. Initial research concluded that a good approach using commercially available technology is through a wristwatch fitted with electrodes that measure the temperature of the skin. Skin temperature is closely related to body temperature and can be used to estimate the core, or body, temperature using a simple equation [12]. This wristwatch technology generally reported temperatures within a few degrees of what was expected by our research team, but we observed frequent errors when it reported measurements which were too far out of the normal range to be considered valid. This fact does not completely disqualify the wristwatch technology for measuring skin temperature in a firefighting situation. Relative increase or decrease in skin temperature is the important consideration of the vital statistic, rather than having the exact reading constantly. To clarify this point, a high rate of change in temperature signals an imminent problem better than a specified temperature zone, since the firefighters are in a high temperature environment. The firefighter already knows he or she is in a high temperature environment; that is the nature of the job. However, the firefighter does need to be informed when there is an unsafe spike in temperature. Accuracy is important, but the general trend of temperature over time is the more meaningful statistic for monitoring firefighter safety.

   After this initial research was conducted, two devices were identified that would meet the defined requirements. Both were wristwatches that had similar means of measuring skin temperature. Manufacturer specifications indicated that both watches had approximately the same level of accuracy for temperature sensing, and therefore the deciding factor was based on passivity and a better expectation of being robust, both in design and Bluetooth connection performance. The first device examined was found to be extremely sturdy in design, as it could be worn in water and had a very small footprint on the user. Internet research indicated that some users had difficulty making the Bluetooth connection, which ultimately became the deciding factor in rejecting the first device, since robust connectivity was a predefined requirement.

   The second device was significantly larger and protruded farther from the wrist than the first device. This point was a detriment, as it increased the chance of the watch being an obstruction on the job, as well as it being impacted by the environment. However, we found fewer reports of connectivity problems with this device in reviews from the initial internet research. A priority call was required between design sturdiness and connectivity sturdiness. After some deliberation, since both devices had no problems with physical breakage during use, the second device, with its better Bluetooth performance record was selected for further investigation.

During our initial hands-on experience with the chosen device, it appeared to record the temperature of the skin fairly well, and the data fluctuated as expected through different levels of activity. Meeting the vital statistics needs for the next-generation firefighter will require a temperature sensor similar to the one in the wristwatch to be integrated into smart clothing of some kind. Benefits from such an approach will include a decreased chance for environmental interference and reduction in the obstruction to wrist movement. Further, the temperature of the chest, as opposed to the wrist, is much closer to actual body temperature and less prone to small fluctuations in skin temperature at the extremities [12].

3.3 Chemical Sensors

The ability to detect potentially harmful chemicals floating in the airspace around a given area can be a useful tool for keeping a safe environment for all personnel. The uses of chemical sensors in firefighting incidents are not as well developed as are other scenarios presented in this report. However, when chemical sensors are implemented, they can deliver a significant benefit to the user in supplying information about the environment.

3.3.1 HAZMAT Use Cases

HAZMAT (Hazardous Materials) units within structural firefighter divisions are often faced with chemical related calls. When one of these calls arises, information about the situation can be scarce; in potentially dangerous situations, it is best to avoid sending in a firefighter to scope out the problem in person, as the reactions may be volatile and unstable. Many of the requirements discussed below will be related to the HAZMAT situations in the *Unmanned Aircraft Systems* section of this report.

When used in a HAZMAT situation, chemical sensors need to be robust enough to work in extreme environments. The sensors should be able to function accurately and effectively in conditions of extreme temperature and exposure to potentially harmful chemicals. If a device were unable to do so, it would be pointless to deploy the sensor; the sensor would not be reliable, and no user would be willing to deploy it.

With regard to accuracy, the critical requirement is that the sensor must be able to detect the necessary chemicals and alert the user when dangerous conditions are present. HAZMAT firefighters require only enough accuracy to determine with certainty whether a situation is hazardous or safe to enter. Specific accuracy requirements across the spectrum of hazardous chemicals are beyond the scope of this project. The inability to determine the safety level of a situation would force HAZMAT firefighters to revert to old techniques.

Beyond accuracy, the device must be able to detect a wide array of chemicals in an environment. Without this ability, the chemical sensor would not be feasible in situations where the firefighters have very little or unreliable information about the potentially hazardous chemicals involved. For example, if the chemical sensor were being used to investigate a volatile reaction, but it could not detect the particular reactants accurately, the user would be lacking critical information for containing the reaction. Thus, firefighters would potentially be placed in hazardous situations. HAZMAT firefighters are, in fact, equipped to deal with these situations, but it is always more advantageous to have complete and accurate information of the situation at hand, especially when the information can be acquired without the potential risk of human life.

Additionally, the chemical sensor should be compact and lightweight. With regard to UAS-carried chemical sensors, if the sensor is too heavy to be carried by the UAS used to transport it, there will be no use for this technology. Even further, if the chemical sensor's weight compromises the user's ability to control the UAS effectively, the UAS, and by extension the chemical sensor, will be rendered useless. Accurate delivery of the device is vital for functional results, therefore any hindrance to the user's ability to modify the device's location is potentially dangerous to all individuals involved.

Similarly, for chemical sensors to be carried by individual firefighters, they must be small enough to integrate effectively with existing PPE. Firefighters cannot afford to be impeded by additional bulky or heavy gear when entering life-threatening situations.

Finally, the chemical sensor should be compatible with other technologies used to collect, relay, and report the data to the user in real time. Devoid of this functionality, the data collected by the chemical sensor would still be of use, but its use cases would be severely limited due to the short time frame of a typical HAZMAT incident. Without real-time information relay, firefighters would be forced to wait for the either the UAS or an individual to return to interpret the data. This delay is impractical for short time frames and would slow the HAZMAT team down significantly.

3.3.2 Structural Use Cases

Even during the event of a normal structural fire (meaning the absence of a HAZMAT situation), firefighters are occasionally exposed to potentially harmful chemicals. Due to this exposure, there is a potential use case for a chemical sensor to inform firefighters about the composition of the atmosphere around them. There are slightly different requirements for the chemical sensors that would be needed for structural firefighters, compared to the chemical sensors necessary for work in HAZMAT situations. Nonetheless, there are certain capabilities required by both sensors. For example, both chemical sensors should be lightweight and fit into a very small profile, regardless of whether the sensor is on an UAS or a part of a firefighter's PPE during a structural fire. As explained previously, UASs have weight limits that are exceeded by some current chemical sensors. Similarly, structural firefighters already carry upwards of 22.5 kilograms of gear. Since interactions with chemicals are rare for structural firefighters, heavy or large sensors are not practical for firefighters to carry on a regular basis.

The design for a structural firefighter's chemical sensor should place a greater emphasis on the robustness of the physical sensor itself. Compared to HAZMAT, structural firefighters are more susceptible to rough movements in the course of their work. The physical sensor should be able to handle large amounts of applied pressure, abrasion proof, and impervious to rough use.

Additionally, the sensor for a structural firefighter should be able to detect lower concentrations of chemicals than the sensor utilized in HAZMAT. HAZMAT firefighters are outfitted to deal with chemical contamination, whereas structural firefighters are outfitted in gear that is meant to combat fire, and they are not as well protected from chemical exposure. A more sensitive device would bring additional certainty as to the condition of the surrounding atmosphere, thereby decreasing the number of firefighters exposed to harmful chemicals due to lack of information. Furthermore, chemical sensors used by structural firefighters do not need to detect as wide a range of chemicals as those deployed in HAZMAT situations. Structural firefighters know with some certainty which chemicals could arise in a structure fire, whereas a HAZMAT team is required to prepare for all chemical situations. The primary chemicals that structural firefighters need to be aware of are chemicals that result from burning household items (clothing, appliances, furniture, etc.) and home building materials (wood, plastics, etc.). Some of these harmful chemicals include carbon monoxide, benzene, sulphur dioxide, hydrogen cyanide, and hydrogen chloride [1]. To summarize, the primary concern for a structural firefighting chemical sensor is sensitivity, covering a defined list of chemicals; a HAZMAT team requires the ability to detect and identify a very broad range of hazardous chemicals.

3.3.3 Current State of Technology and Future Endeavors

1. **HAZMAT Devices**
   After conducting initial research, it was found that there are no commercially available solutions that meet the requirements listed above. A chemical sensor with the specifications listed for HAZMAT use cases does not exist at this time. In particular, the obstacles lie with the inability to detect and identify a wide range of chemicals while constrained to a lightweight and compact design. This gap poses a serious problem, as the current understanding of the implementation of this technology is dependent on both requirements. If the sensor is too large, it will inhibit control of, or exceed size and weight capacity of, an UAS. In order for the technology to advance and make this idea feasible, the chemical sensor industry will need to develop strategies to reduce significantly the size of each sensor. Without innovation, the technology will not be feasible for use on a HAZMAT UAS device.

   Furthermore, industry innovation is needed for a more universal chemical sensor supporting a wide variety of applications before the technology can be useful to HAZMAT teams. Current chemical sensors capable of measuring multiple gases also are generally fairly slow in their readings, and once they have detected a harmful chemical, they are unable to detect quickly a decreased level. Chemical sensors for the next-generation first responder need to be able to detect the presence, increases, and decreases of levels of a broad range of harmful chemicals quickly and dynamically. This capability may require development of a completely different technology in order to compress a chemical sensor to the size necessary for HAZMAT applications. In the absence of any options for sensors which would meet our requirements, the team was not able to provide a hands-on evaluation.

2. **Structural Devices**
   Investigating chemical sensors for structural firefighting scenarios required little effort beyond the work already completed for HAZMAT incidents. Because the requirements for both scenarios were similar, again there were no commercially available technologies which would meet the requirements discussed above. As in the HAZMAT case, significant innovation in the size of the sensing device will be required. In contrast to the HAZMAT scenario, the structural case does not require sensing a broad range of chemicals. Weight is still a problem, since combing chemical sensors into a package with current technology yields a solution too heavy for structural firefighters to carry without inhibiting movement.

   Initial research revealed few chemical sensors that were rugged enough to be feasible for structural firefighters. New development work from industry is required, because a sensor that is not reliable in harsh conditions will not be adopted by firefighters. Overall, for chemical sensors to be relevant for the next-generation firefighter, much innovation is needed. As in the case of HAZMAT chemical sensors, there were no similar chemical sensors available for evaluation.

3.4 Hearing Protection

Early in our investigation, the request for hearing protection was presented to the research team by local firefighters. Several local firefighters were already using hearing protection technology, self-funded (not issued by the fire department or the government). The firefighters realized hearing loss was prevalent among individuals on the force, with as many as 36 percent of firefighters indicating moderate to severe hearing loss [4]. Thus, many were trying preventative measures prior to experiencing any real negative changes in their hearing.

Firefighters are exposed to excessively loud noises on a routine basis. The Occupational Safety and Health Administration (OSHA) and its partner, the National Institute for Occupational Safety and Health (NIOSH), recommend an exposure rate of no more than 85 dBA (A-weighted decibels) for a continuous 8-hour time period [15][18]. Both OSHA and NIOSH scale this recommendation. For every 3 dBA noise level increase over 85 dBA, the 8-hour time recommendation should be cut in half [15][18]. Applying this guideline, a firefighter in a fire station with an average noise level of 88 dBA, the low end of the typical range during equipment testing [15], should only be inside the station for 4 hours. Unfortunately, firefighters exceed this amount easily during a typical 48-hour on-call shift. On any given day, firefighters are exposed to high noise levels from fire truck sirens, fire alarms, loudspeakers, and possibly roaring fires which range in noise levels from as low as 67 dBA to as high as 116 dBA [15], easily exceeding the recommendation. Moreover, firefighters are on-call for 48 consecutive hours, far surpassing the 8-hour maximum even before scaling. The need for hearing protection is obvious.

Firefighter personnel need to be aware of their surroundings, able to communicate with other responders in the area, and able to hear vital information effectively from the radio connection. To that end, firefighters require a device that can protect their hearing without hindering important environmental sounds. The device must be passive, with comfort and the secure placement of the earpiece established as high priorities in order to allow use over extended periods. In this section, the idea and feasibility of using earplugs to accomplish this delicate task will be discussed.

3.4.1 Current State of Technology and Future Endeavors

Essentially, firefighters need earplug-like devices that dampen excessively loud noises while maintaining clear perception of low and normal range sounds in a comfortable and secure design. Currently, a range of products are available that claim to offer this level of protection using combinations of noise canceling technology, audio compression, and acoustic filters. We conducted a preliminary investigation into a small sample of currently available products through internet research and interviews to determine their viability and practicality for firefighters and other first responders.

Noise-canceling technology was immediately deemed to be too constrictive for firefighter purposes. Although preventing hearing loss, noise-canceling devices would prevent firefighters from communicating with nearby personnel and from hearing their radios. Thus, however helpful in preventing hearing loss, the technology would impede the firefighter's work, and might jeopardize his or her safety, on the scene of an emergency.

Next, hearing protection solutions were investigated. One solution was to reduce decibel levels by a range of 7 to 13 decibels defined on the Noise Reduction Ratings system as seen in foam earplugs [16]. Alternatively, audio compression devices reduce loud noises to a manageable level while attempting to retain normal and lower range hearing. However, these devices, by nature, contain many small pieces encased in an already small earbud. If any pieces are damaged or broken, parts are often difficult to replace. In the daily execution of a firefighter's work, the probability of damaging the delicate electronics system located inside a small earbud used in harsh environments is high, and the maintenance is not ideal as it may require replacement of small parts. In view of these factors, another solution is preferred.

Some of the digital hearing protection solutions also require an external battery or use power through a connected device such as a phone, radio, or tablet. Drawing power from other devices on the firefighter, or forcing the firefighter to carry additional battery packs or replacement batteries, can and should be avoided when possible. Ear-canal devices may meet the same requirements without adding weight to the already heavy gear carried by the first responder. In any case, if the battery dies while the firefighter is inside a building with no means of changing the battery, hearing protection and possibly radio communications will be compromised. In summary, the use of small electronics in an earbud apparatus would require maintenance, careful protection, and a high reliability.

Finally, the third method explored was acoustic filters. Much like the audio compression devices, the acoustic filters provide protection by suppressing high-level noises while passing quieter sounds to the user, but they do not require electronic maintenance or additional electronic elements. Due to their passive nature and design, many earplugs containing acoustic filters are more durable. Acoustic filters, by definition, pass sounds in a specific range of frequency, while rejecting sounds outside of the range using a combination of low and high pass filters. The design of an acoustic filter for a noise-reduction application provides increasing attenuation with increasing noise levels. Acoustic filters by their nature cannot discriminate between quieter and louder sounds as well as digital solutions, and therefore they tend to block out more "desirable" sounds while protecting users from high sound levels; however, they are still valid options for consideration.

Another point of concern is the ability to keep earbuds secured inside of the ear. Firefighters move quickly throughout the day, donning masks, helmets, and over-the-ear headphones multiple times a day. Fidgeting with an earbud while important tasks require attention is bothersome. Eventually, the problem with security in placement could outweigh the long term argument for hearing protection, and the technology could be cast aside.

In our search for earpieces with filters of any kind, we found three types of ear tips that secure the earpiece inside the ear: foam ear tips, silicone hemisphere tips with two or three stacks, or custom molded silicone ear tips. Foam ear tips are usually found in simple earplugs blocking all noise levels or as part of an audio compression device. Due to the construction of this type of earpiece, the earbud portion connected to the ear tip extends outside the ear canal, and occasionally beyond the external part of the ear. As a result, the earpiece is more likely to fall out or be jostled out of position during performance of the firefighter's active tasks.

The silicone hemisphere stacked ear tips are available in multiple sizes to account for differences in ear canals and ear sizes, providing a more secure placement inside the canal. Even with a good fit, the filter, whether electronic or acoustic, is housed in the earbud portion of the earpiece. As with the foam ear tips, the earbud portion extends out from the ear creating a higher likelihood of external objects altering the position of the earpiece, or knocking it out entirely.

The custom molded silicone ear tip is molded to each individual ear and does not extend beyond the external ear. The entire earpiece lies flat or concave within the ear and is inserted a small distance into the ear canal. The appropriate filter is embedded within the silicone mold, so nothing extends outside the ear. Since the entire earpiece, both ear tip and earbud, are conformed to the individual's ear and are flush with the ear, external objects are less likely to alter the position of the earpiece. Moreover, the custom fit earpiece feels natural to the user, and therefore, is more comfortable. Thus, a custom fit earplug or equivalent device is ideal in terms of security and comfort. Unfortunately, individually fitted pieces may not be shared among team members in the case of an emergency. A firefighter may have backup earpieces, but he or she would likely be unable to share with colleagues in the event of a lost or broken earpiece. Generic molded earpieces would have to be made and placed in reserve for contingencies.

Given the initial research investigation detailed above, two custom molded, acoustic filter earpieces were acquired with the intent of obtaining hands-on experience and direct feedback from local firefighters. One of the earpieces was purchased with a built-in direct connection for current firefighter radios using a 3.5 millimeter threaded connection. In the resulting configuration, one ear has a custom molded earpiece with an acoustic filter that is connected to the radio directly. When used, the radio feed was loud and clear for the user. The second earpiece was custom molded with an acoustic filter but without capability to connect to the radio. Upon receiving the devices, we found that the first, smaller, radio-fitted earpiece was comfortable for longer periods of time than the larger, second earpiece. The second earpiece was made out of a quick setting silicone, rather than the lab-constructed silicone of the first earpiece; consequently the difference was measurable when wearing the device. Ideally, two of the custom fit silicone earpieces would be worn, with one with an acoustic filter and direct connection to the radio and one with only the acoustic filter.

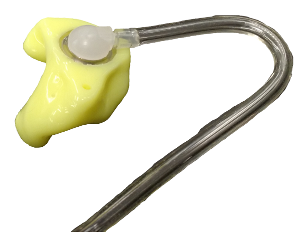

Figure 6: Custom acoustic filter ear bud with radio attachment.

The interviewed firefighters who were using hearing loss prevention devices were primarily using custom molded, acoustic filter, and radio-connected earpieces. Their experience provided an initial direction for the research team and an available pool of testers. The firefighters reported that their earpieces were comfortable and secure in the ear all day, provided adequate noise blocking capabilities with clear radio feeds, and allowed face-to-face communication. Firefighters using such devices indicated that the earpiece connected directly to the radio was worn when the radio was in use. A second, independent earpiece was used in loud environments or during non-paramedic situations, but it was carried by the firefighters at all times.

Hearing loss prevention is an important part of the health and safety of the next-generation first responder. Although the currently available devices should effect reductions in the rate of hearing loss in users, a couple of adjustments could be made to develop the technology into truly outstanding equipment. First and foremost, when the earpiece is in, the ability to communicate verbally with other personnel in the immediate area, under noisy conditions, is crucial. The earpiece could be modified to enhance this ability while maintaining a high level of protection against high noise levels. The performance of the filter might be customized for a better user experience and ultimately higher protection in typical firefighting environments. Opportunities for collaboration with NIST might be explored in researching audio intelligibility standards for firefighters using different hearing protection devices. The PSCR lab on NIST Boulder's campus has already performed significant research on audio intelligibility for radio communication [19].

3.5 Electroluminescent Tape

As discussed earlier, visibility is vital in a firefighter's line of work. On a large scale, UASs and body cams provide firefighters with a broad overview of the area. On a smaller scale in low visibility situations, firefighters rely on reflective material, or trim [17], attached to their bunker gear to see one another. Although the current trim is helpful, it is not a perfect solution. Trim reflects light, and as ambient light is not always available in smoky or dark conditions, better choices may exist to suit the needs of firefighters. In this section, the possibility of outfitting firefighters with higher visibility in dark conditions is discussed.

3.5.1 Wildland and Structural Use Cases

Wildland firefighters work in a variety of outdoor areas including forests, mountainous regions, brush, and grasslands. Some of these landscapes, such as trees in forests, may obstruct the firefighters' field of vision, specifically at night when trying to locate other firefighters in the distance. Conversely, structural firefighters are in close proximity to one another, but their visibility is limited due to smoke. In both cases, firefighters need a bright and efficient way to locate one another visually without the aid of a camera.

Luminescent products can be used to illuminate individuals, fire trucks, fire hoses, and other equipment. As stated above, visually locating firefighters, whether in outdoor conditions or inside smoky buildings, is difficult. Thus, properly illuminated bunker gear is vital to each firefighter's visual understanding of where teammates are located. Furthermore, in car crash incidents, civilians in the area need to be able to identify easily both the firefighters and emergency vehicles to avoid collision. Moreover, fire hoses clearly marked with a luminescent product would enable firefighters to find exits from inside a building more efficiently, potentially saving lives. Illuminated fire equipment would also be easier to find if dropped inside a building under dark conditions.

First and foremost, a luminescent product must increase the visibility of the attached item, through intense conditions. Inside a smoke-filled building it is common to be unable to see clearly more than 15 centimeters away. Providing visibility at greater distances in these environments is a key feature for this technology. The product would be attached to people or mobile objects, therefore, the luminescent product must have the flexibility to move with the person or item. Rigid construction would hinder the firefighter's mobility, reducing the overall effectiveness of the fireman. Moreover, fire hoses and other fire equipment require some degree of mobility as well.

Durability is another key factor in product selection. The luminescent product would be exposed to diverse climate conditions and rugged, everyday use. The product must be able to withstand harsh conditions with very little long-term maintenance. Lastly, the product needs to be capable of implementation in a variety of materials and gear. Firefighters, fire trucks, fire hoses, and other related gear require high visibility for safe fire operations. The solution must work universally and reliably for all items.

3.5.2 Current State of Technology and Future Endeavors

Two current options for reflective materials are photoluminescence (PL) and electroluminescence (EL). Both options are brighter than current reflective materials, but they have different charging mechanisms.

Photoluminescence outputs a brighter "glow" effect than current reflective materials by absorbing and storing photons from ambient light to be emitted in a glow fashion at a later time. This means that the device, whether paint, tape, stick, or rope, must be "charged" by outside light sources prior to use. Although this type of luminescence does not require a battery source, it does require charging. A cluster of problems can be derived from this type of charging requirement. Firefighters may not have time to charge the device ahead of time, and they often have multiple back-to-back calls over the course of a day. Their devices, tools, and equipment must be ready constantly; at minimum, the device must have replaceable power sources, or the user must have the ability to change out the device itself in a timely manner. Waiting an indeterminate amount of time for safety devices to charge in an emergency is impractical and life-threatening. Retaining a back-up photoluminescent device in the fire truck is unreliable due to the nature of the charge associated with the equipment. Therefore, although the brightness of photoluminescence is superior to that of the current reflective material, the reliability and practicality of photoluminescent devices falls short of current materials.

Electroluminescence, on the other hand, retains the same level of brightness as the photoluminescent devices, and it does so without charging problems. Electroluminescent devices are powered by battery packs or wall sockets and come in a range of products including rope, paint, and tape. The obvious, overall downside to this type of device is the need for battery packs. As described in earlier sections, firefighters carry an abundance of tools and equipment, therefore adding the weight of another battery pack is an immediate problem. Nonetheless, electroluminescent devices could be connected to the current battery packs on the firefighters' SCBA units. Using this connection, the electroluminescent device would provide better visibility for the firefighter with a minimal amount of extra weight. Considering these factors, the team analyzed three electroluminescent devices.

Electroluminescent rope is the least viable of the three options. The rope is stiff, difficult to move, requires charging prior to use, and must be carried into the incident area like the fire hose. The rope is stored on a spool much like a garden hose and is normally charged via a wall socket instead of a battery source. All of the traits associated with electroluminescent rope, aside from illumination, are problematic for firefighters.

Unlike electroluminescent rope, electroluminescent paint can be applied to any surface and is moderately flexible. The paint is evenly spread across the desired surface and connected to a power source to cause illumination. Electroluminescent paint is marketed through two channels: do-it-yourself (DIY) and custom. The DIY paint kit consists of multiple bottles of paint and a battery pack. The user must paint the appropriate section of material with each bottle of paint in a specific order indicated by the instructions, and then attach the battery pack. Although the process is tedious and time-consuming, if done correctly, it should provide to the user an inexpensive, battery-powered, electroluminescent-covered product. Unfortunately, this procedure leaves excessive room for user error. If the user does not apply the paint properly in uniform, cohesive layers, the final product may be faulty. Gaps in paint or improper battery connections could cause only a portion of the painted surface to illuminate. In either case, the resulting product would be only partially operable. Moreover, it is not practical to expect firefighters to paint by hand every surface in need of illumination.

Custom electroluminescent paint brings forth a different set of problems when compared to the DIY project. Custom-painted electroluminescent products are sent to the manufacturer, painted with an air brush for an even coat, and returned. As with the DIY paint, the custom paint may break or chip, harming the integrity of the overall piece. Breakage is less likely with the professionally painted product, and the higher durability comes with increased cost and delivery time. The whole process takes upwards of three weeks due to the scarcity of professionals able to paint the products and the backlog on orders. Moreover, the price is over ten times that of the DIY kit. Thus, although firefighters would be guaranteed a quality product, most departments do not have the money to support such an expensive endeavor.

To avoid chipping or partial breakage, electroluminescent tape deserves consideration. Electroluminescent tape is manufactured with adhesive on one side and electroluminescent material on the opposite. The battery-powered device eliminates the partial working problem evident in DIY electroluminescent paint (or less often, professional electroluminescent paint) as each device segment is sealed. The tape is available in a variety of lengths, widths, and colors. Each section of tape is connected to a battery source and illuminates when powered on. Moreover, the tape is easy to install, as it merely requires removing the adhesive protection layer and mounting the tape to the desired surface. The tape is moderately flexible, therefore the firefighter's range of motion should be minimally impacted, if at all.

Firefighters who were interviewed were open to the idea of a better illuminating device; however, they posed questions and concerns regarding the products provided to them for consideration. First and foremost, firefighters were concerned about weight from additional battery packs. Neither wildland nor structural firefighters want to carry additional battery packs. Second, structural firefighters were concerned about practicality. Specifically, most of the structural firefighters' concerns pertained to the durability and consistent visibility of the electroluminescent tape: hoses are dragged through mud, water, dirt, soot, and a variety of other substances, thus the tape could easily get coated in any number of things during one call. As a result, the tape, or any other illumination device, would be rendered ineffective.

For electroluminescent tape, or any other kind of illuminating device, to be practical for a large-scale fire department, the above stated problems must be addressed. Battery packs for these devices must be minimized or integrated into battery packs already carried by firemen. However, integration into current battery packs requires analysis of power capacity and consumption. If the electroluminescent tape significantly decreases battery life, probably another solution or power source should be used. The illuminating device must be visible regardless of the situation and condition of the device, remain properly attached, and require little or no maintenance. Beyond these criteria, if electroluminescent tape is used, it must be flexible enough to move with the firefighter and not restrict his or her movements. On the other hand, if an electroluminescent paint is used, safeguards need to be incorporated to ensure all parts of the paint are connected to the battery at all times. Electroluminescence is promising technology, but it has a multitude of problems to be resolved before mass distribution and implementation will be feasible.

3.6 Cooling Clothing

Both wildland and structural firefighters are exposed to excessive heat and perspiration from sources other than fires. Whether trekking under a hot sun with 20 to 43 kilograms of gear strapped to one's back, or encased in bunker gear for hours at a time, a firefighter needs to be dry and cool to function at his or her highest level for extended periods. A lightweight, practical cooling mechanism can be used to cool the body without impeding movement or range of motion for firefighters. In this section, current options for body cooling technologies are discussed.

3.6.1 Wildland Use Cases

Due to the nature of their jobs, wildland firefighters often hike through forested, and possibly mountainous or rugged terrain with backpacks containing supplies to sustain them for at least 24 hours in the area. Speaking with the focus group, the research team found that wildland firefighters carry 20 to 43 kilograms each of necessary provisions, tools, and equipment at all times including food, water, radios, flashlights, batteries, ropes, tents with heat protection, chainsaws, fuel for chainsaws, extra clothing, safety glasses, matches, and emergency flares regardless of the season, weather, or time of day. While physically exerting oneself in rough outdoor terrain with added weight, staying cool and dry is imperative.

Since wildland firefighters work in an active, outdoor environment, there are certain requirements which cooling clothing must maintain to be practical. First and foremost, the clothing must be light, yet durable. The fabric should not add weight to the firefighter's already heavy load, but it must be able to withstand harsh, everyday use. Secondly, the clothing must be flexible and not inhibit the mobility of the user. Wildland firefighters require a full range of motion for their everyday activities, and any hindrance to that ability will probably outweigh the alternative benefits of the product. A final requirement for the cooling clothing is compatibility with the firefighters' existing gear. The product should not interfere with any current gear, but rather enhance each firefighter's overall performance.

3.6.2 Structural Use Cases

Structural firefighters are exposed to a different kind of exertion and heat from wildland firefighters. Structural firefighters, including HAZMAT teams, are encased in heavy bunker gear. Although the multiple layers of the bunker gear protect the fireman from extreme heat and the fire itself, the material creates an insulation layer, trapping body heat and perspiration. Cooling down the interior of this type of gear would enable firemen to be more comfortable and safe from overheating, enabling them to stay inside the gear for longer periods of time.

Despite the differences in environments, the requirements for a structural firefighter's cooling clothing is very similar to the wildland requirements. The clothing must be light, durable, flexible, and provide mobility for the user. Additionally, the product must supplement the current firefighter gear without hindrance. Since structural firefighters would wear bunker gear over any theoretical cooling clothing, the fabric must be able to cool the firefighters successfully within the enclosed environment of the firefighter's bunker gear.

3.6.3 Current State of Technology and Future Endeavors

Since cooling the entire body at the same time is impractical in an active environment, the main portion of the body, the upper body (torso), was the focus for the project team. After preliminary research, three primary types of upper body cooling methods were found: ice pack garments, cold water tubed garments, and special woven garments. The three techniques provide varying levels of cooling ability, flexibility, weight, and reliability.

Ice pack garments have two main variants. The first variant has two separate parts: the ice packs and a clothing piece. The ice packs must be frozen prior to use, then secured on the clothing piece via pockets in the garment, Velcro, or other means. The second variant is a singular clothing piece with large gel packets sewn into the cloth itself. Prior to use, the whole garment must be placed in a freezer to cool (with the intention of freezing the gel packets). When frozen, the clothing becomes rigid against the body, hindering flexibility and mobility. Over time, the ice packs or gel packets reach ambient temperature, melt, and lose their cooling effect. After melting, the ice packs and gel packets return to the liquid state with no positive cooling effects–adding weight to the fireman with no added benefits. Moreover, in the event that one or more ice packs or gel packets need to be replaced, there is no freezer available in the woods (wildland) or on scene at a fire (structure) to prepare replacements.

The second method, cold water tubed garments, suffers from many of the same problems as ice pack garments. Cold water tubed clothing consisting of tubing (varied sized tubing depending on company, manufacturer, and personal preference) attached via sewing, Velcro, or adhesive to a garment with a battery pack, pump, and water cooling device attached. The battery pack and pump force water, cooled by the water cooling device, through the tubing to create a cooling effect for the user. Much like the ice pack clothing options, the tubing creates a rigid garment that limits flexibility and mobility. Due to the number of parts and pieces in the system, the number of points of failure increases and the reliability of the device decreases. Additionally, the battery pack, pump, and water cooling device add a significant amount of weight and bulk to the firefighter's already loaded pack. Despite these problems, this cooling system does not lose its cooling effect over time like the ice pack garments. The limiting factors are not the water or ambient temperature, but rather the life of the battery and the system components.

Finally, the specialty woven garments have multiple variations with a few common traits. Many of these garments are marketed as athletic garments used to cool the body during physical activity. Most of the specialty woven garments have wicking fabric sewn into the garment, ultraviolet (UV) protection ranging from 30+ UPF (ultraviolet protection factor) to 50+ UPF, and odor protection. The wicking fabric works to distribute moisture (most commonly perspiration or water) on the body garment to enable the liquid to evaporate faster, drying the user and creating a cooling effect. The wicking characteristic is useful in outdoor situations such as wildland fires, or in everyday firefighter activities. However, wicking would not work properly underneath bunker gear or a HAZMAT suit.

Beyond the previously listed traits, some products had additional properties to help cool the user, including polymer-activated sweat rings, xylitol woven into the garment, or 3D aluminum spheres woven into the garment. Garments with the polymer-activated sweat rings had the rings incorporated into the garment to face the user's skin for direct contact. The rings absorb moisture from the skin (most commonly sweat) and create a raised effect on the skin's surface. The raised effect enables air to flow between the user's skin and the garment to cool the surface temperature. Additionally, the polymer inside of the swollen ring reduces the temperature of the sweat captured by the ring. Garments with xylitol, a compound found in birch trees, react with water, and manufacturers claim to cool down the skin's temperature by up to 15° C. Finally, garments with 3D aluminum spheres woven into high sweat areas are intended to become wet and cool down when in contact with wind gusts. Much like the wicking characteristic, the 3D aluminum spheres are more effective in an outdoor environment.

In interviews, firefighters indicated that cooling inside bunker or HAZMAT gear was a high priority. Some HAZMAT teams are taking primitive measures, like taping ice packs to firefighters before suiting up to help them stay cool. The firefighters suggested a need for a more practical solution in the form of cooling clothing.

For any type of cooling clothing to be useful for firefighters, the clothing must be tested in both outdoor conditions and beneath bulky bunker gear. The clothing must wick away sweat efficiently and cool the user simultaneously. Additionally, the technology must be merged with the biometric smart clothing presented earlier in this paper to create one uniform garment.

Figure 7: Cooling garment with wicking features.

4 Lessons Learned

Throughout the process of documenting the next-generation firefighter project, many overarching themes related to the research, technology, and policies regarding the technology became evident that did not fit into the main structure of the report. In this section, we discuss these additional ideas, as well as information that did not necessarily pertain to any section, but was helpful knowledge accumulated during the data-gathering process.

4.1 Stakeholders

Meetings and discussions with the BFRD proved to be instrumental to the overall development of the project. The firefighters provided information with respect to what the firefighters believed they were missing in regard to technology, and they also provided information on which technologies they would be more cautious to adopt. For example, when interviewing the Fire Chief of BFRD, we learned that there are not only cost-related and feasibility-related problems, but also more administrative problems involved in implementing certain technologies, such as the UAS potentially violating 4th amendment rights. Knowing that there were hesitations about certain technologies inspired research that was more comprehensive and helped develop technological requirements that would better satisfy the needs of the firefighters.

As further research into the next-generation first responder is conducted, stakeholder involvement is pivotal. Strong currents of communications between the developers of the technology and its users will guarantee more comprehensive technology that will actually be adopted by those for whom it is created. For other technologies where first responders are hesitant, education, training, and demonstrations will be key to full integration.

4.2 Technology and Policy Developments

The technologies discussed in this paper do not span all of the responsibilities of a firefighter. Many other areas of the job can be improved. For various reasons, the technology related to these areas was not purchased. Below is a short description of additional improvements which might be considered as additions to a firefighter's arsenal.

4.2.1 Power Alternatives

For mobile devices, power is always a concern. In many of the sections listed above, the firefighters were concerned about the additional weight of battery packs. Many times, power supplies such as batteries are the heaviest items in the firefighter's arsenal. For example, wildland firefighters in BFRD carry 50 additional AA batteries in each individual's backpack to use as replacements in each of the carried devices. The average weight of 50 AA batteries is 1.1 kilograms. With advances in power technology, carrying over one kilogram of a finite, disposable resource seems counterproductive when rechargeable power resources are available. Mobile power stations, such as solar energy, and hand cranks, could be viable replacements for at least some of the 50 AA batteries. Solar panels could hang on an individual's backpack, facing outward, to charge devices as the wildland firefighter goes about regular business. In dark outdoors conditions, however, this device would be rendered useless. Hand cranks would be used during down time or cases without light. Hand cranks take more time to charge a device and require manual motion, not ideal for a fireman's line of work. Ultimately, carrying 50 AA batteries is not efficient, and other solutions are available, even if not yet fully functional to firefighter standards.

Many considerations must be examined for improving efficiency of powered devices. First, policy needs to be developed creating universal sources for battery power on firefighter equipment. Currently, most devices run on AA batteries, so the firefighters do not have to carry multiple different types of power supplies. The future of power technology must maintain this level of uniformity. Second, solar technology must improve for creating more efficient charging devices. During our research, we found no portable solar or mechanical power supplies which were powerful or rugged enough for firefighting applications. The amount of energy currently available devices could provide for firefighter equipment in 10 hours of direct sunlight was enough to power the GPS tracking tool discussed earlier for only 8 hours. This GPS device is only one piece of equipment that firefighters would carry; they will need other power supplies for all their associated gear. Clearly, currently available systems would need work before being viable for implementation

4.2.2 Thermal Imaging Cameras

Thermal imaging cameras are incredibly useful to firefighters. Much like a normal camera, a TIC can take pictures and video and stream live video from an incident area. The resulting images show the heat signatures of everything within the frame, which is useful information for identifying fires, high risk burn areas, trapped individuals, or cold spots in a building. Unfortunately, due to the cost of TICs, even well-funded fire departments only purchase one TIC per fire truck or engine instead of one per firefighter. Moreover, most TICs are heavy, weighing over 0.68 kilograms per device, which can be an impractical weight to add to the firefighter's pack. If one ignores the weight addition, another problem arises: the ability to use the device. Most TICs are handheld; firefighters are often feeling for survivors, touching the wall or hose to retain an exit path, and using a multitude of other tools. Thus, an ideal TIC would be more cost-efficient, hands-free, and lighter for personal use.

From a broader point of view, as discussed earlier, TICs could be used in applications on UASs, HUDs, or body cams, solving the hands-free problem. The live feed could be relayed to the Incident Command Post or to a hands-free device such as a HUD for individual firefighters. Likewise, if the TIC were mounted on an UAS, additional weight would not be added to the firefighter. For such a system to be implemented, the TIC would need to be light and small enough to fit on an UAS. Unfortunately, this would do little to ease the already high cost of TICs.

4.2.3 General Policy Development and Stakeholders

The proposed solutions for the next-generation firefighter must be tackled on two fronts: technology and policy. This paper primarily focuses on technological developments, but here we briefly discuss some policy implications for much of the explored technology.

Although UASs are an amazing tool with multiple applications, if firefighters are unable to use the devices due to airway restrictions, the technology is useless. Body cams can be crucial in giving the ICP a firsthand look at the problems firefighters face inside a building. However, both body cams and UASs have issues regarding privacy. As UASs and body cams would be used to film inside of commercial and civilian structures, any recorded video would become public domain, regardless of consent from civilians and companies to film inside their homes and businesses. Policy would have to be adapted to allow such technologies to be used while protecting citizen rights.

Furthermore, some fire departments are concerned about changing the "tried and true" way of the firefighters, meaning they are hesitant to adopt new technologies in most cases. When fighting a fire, relying on technology that suddenly fails can cost lives, and firefighters tend to prefer methods that have as few points of failure as possible. Although the current procedures are effective, technology devices can provide firemen with more efficient, faster, and safer methods for accomplishing their job. These devices can be used in combination with existing methods to improve overall firefighter health and safety at no additional risk.

5 Conclusion

Developing the next-generation first responder involves completely overhauling the existing first responder with regard to communications technology. Integrating the old standards of radio frequency (RF) technology with the improving broadband and LTE technologies enables first responders to be connected, protected, and fully aware.

There is a large body of strategic information that could be delivered to the Incident Command Post during fire emergencies and would aid in firefighting and containment. Through some of the devices and implementation strategies explored in this paper, a few potential points of interest for further research were discovered. As UASs become more prevalent in emergency situations, compatibility with a range of technologies such as TICs and chemical sensors will be imperative. There is also much work that must be done regarding policy surrounding UASs. Similarly, live streaming body cameras could be instrumental in firefighting scenarios, but policy issues must be acknowledged in terms of civilian and corporate privacy. In the area of GPS and tracking technology, wildland firefighters need GPS solutions that communicate across units seamlessly, passively, and in real time. All information from the above technologies must be passed to the IC in a streamlined and absorbable manner.

Likewise, there is a vast amount of information that could be delivered to both the Incident Command Post and individual firefighters in regard to maintaining firefighter health and safety. Biometric information about firefighters has the potential to identify high risk individuals quickly in a manner that could save lives. Work is needed for reporting this information to a singular database in real time as relevant data for the IC, while also reporting to the affected individual. The information must be simultaneously readable and unobtrusive. Information could be displayed to individuals through devices such as Heads-Up Displays; however, work must be done to develop HUDs that are durable and do not obstruct firefighter vision and focus on the job.

Ultimately, this paper presents a list of consumer-available technology with capabilities that would be helpful to today's firefighters. The technology is not fully developed, nor is it ready for firefighter use, but it is the hope of the research team that this paper will encourage research in the correct direction for advancing public safety communications technology. Firefighters and first responders need to be protected, connected, and fully aware so that they can accomplish their jobs in a safe and efficient manner.

References

[1] Brandt-Rauf, P. W., L. F. Fallon, T. Tarantini, C. Idema, and L. Andrews. "Health Hazards of Fire Fighters: Exposure Assessment." British Journal of Industrial Medicine. U.S. National Library of Medicine, n.d. Web. (http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1009663/).

[2] "California Public Records Act." (n.d.): n. pag. Web. (http://www.thefirstamendment.org/publicrecordsact.pdf).

[3] "Colorado Open Records Act (CORA)." Colorado Open Records Act (CORA). N.p., n.d. Web.

[4] Ewigman, B G et al. "Efficacy of an Intervention to Promote Use of Hearing Protection Devices by Firefighters." Public Health Reports 105.1 (1990): 53–59. Print.

[5] "Family Radio Service (FRS)." Federal Communications Commission. N.p., 2015. Web.

[6] "Fire Department Calls." National Fire Protection Association. N.p., Sept. 2014. Web. (http://www.nfpa.org/research/reports-and-statistics/the-fire-service/fire-department-calls/fire-department-calls).

[7] "Firefighter Fatalities in the United States." Firefighter Fatalities in the United States. U.S. Fire Administration, n.d. Web. 23 July 2015.

[8] Firefighter Fatalities in the United States in 2013 / USFA & NFFF. Emmitsburg, MD: U.S. Fire Administration, 2013. U.S. Fire Administration. Nov. 2014. Web.

[9] Garimella, Mihir. "Designing the Next Generation of First Responders." TEDxTeen. N.p., n.d. Web. (http://tedxteen.com/talks/tedxteen-2015-nyc/298-mihir-garimella-designing-the-next-generation-of-first-responders).

[10] Jinesh, Mathew, Yuliya Semenova, and Gerald Farrell. "A Miniature Optical Breathing Sensor." Biomedical Optics Express, 2012. Web.

[11] Karter, Jr., M. J. 2014. Fire Loss in the United States During 2013.
Quincy, MA: National Fire Protection Association.
(http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1191.pdf)

[12] Lenhardt, R., and DI Sessler. “Estimation of Mean Body Temperature from Mean Skin and Core Temperature.” National Center for Biotechnology Information. U.S. National Library of Medicine, Dec. 2006. Web. (http://www.ncbi.nlm.nih.gov/pubmed/17122574).

[13] “Maintenance, Safeguards, and Operational Features for Exit Routes.” Occupational Safety and Health Administration. N.p., n.d. Web.

[14] Miller, Lindsay, Jessica Toliver, and Police Executive Research Forum. “Implementing a Body-Worn Camera Program.” (2014): 32. Community Oriented Policing Services. The United States Department of Justice. Web. (http://www.justice.gov/iso/opa/resources/472014912134715246869.pdf).

[15] NIOSH. “Promoting Hearing Health Among Fire Fighters.” Publication 2013-142, Promoting Hearing Health among Fire Fighters (2013): n. pag. May 2013. Web. (http://www.cdc.gov/niosh/docs/wp-solutions/2013-142/pdfs/2013-142.pdf).

[16] “Noise Reduction Ratings Explained.” Cooper Safety Supply. N.p., n.d. Web. (http://www.coopersafety.com/noisereduction.aspx).

[17] O., Jeffrey, and Grace G. Stull. “Focus on Turnout Gear Visibility.” FireRescue1. N.p., 16 July 2008. Web. (http://www.firerescue1.com/fire-products/Personal-protective-equipment-ppe/articles/419961-Focus-on-Turnout-Gear-Visibility/).

[18] “Occupational Noise Exposure.” Occupational Safety and Health Administration. N.p., n.d. Web.

[19] “PSCR Releases Audio Files for Intelligibility Testing.” PSCR Releases Audio Files for Intelligibility Testing. NTIA, 31 May 2013. Web.

[20] Purohit, A., and Z. Sun. “SensorFly: Controlled-mobile Sensing Platform for Indoor Emergency Response Applications.” Carnegie Mellon University. N.p., n.d. Web.

[21] “Standard Firefighting Orders and 18 Watchout Situations.” U.S. Forest Service. N.p., n.d. Web.

[22] “What Is High Blood Pressure?” National Heart, Lung, and Blood Institute (NIH). N.p., n.d. Web. (http://www.nhlbi.nih.gov/health/health-topics/topics/hbp).

[23] "Wildland Fire Summary and Statistics Annual Report 2012." (2012): n. pag. National Interagency Fire Center. Web.

[24] "Yarnell Hill Fire Serious Accident Investigation Report." (2013): n. pag. Wild Fire Today. 23 Sept. 2013. Web.

[25] Zhang, Pei. "SensorFly: A Minimalist Approach for Emergency Situational Awareness." Awareness Magazine (2013): n. pag. Web. (http://www.awareness-mag.eu/pdf/003986/003986.pdf).